M 113

The Amateur's Telescope

BY

REV. WM. F. A. ELLISON,
M.A., B.D., F.R.A.S., F.R. Met. Soc.

R. CARSWELL & SON, LTD., PRINTERS, QUEEN STREET, BELFAST.

THE AMATEUR'S TELESCOPE

BY THE

REV. WM. F. A. ELLISON,

M.A., B.D., F.R.A.S., F.R.Met.Soc.

Director of Armagh Observatory.

Member of the British Astronomical Association, and of the Societe Astronomique de France.

Belfast:

R. CARSWELL & SON, LTD., QUEEN STREET.

—

1920.

CONTENTS.

Chapter		*page*
I.	Introductory—Literature	11
II.	Tools and Materials—Edging—Rough Grinding	13
III.	Testing; Foucault's Shadow Test ...	22
IV.	Polishing	28
V.	Figuring—Parabolising by Graduating Facets —The Small Polisher System—Parabolising by Overhang—Working Uphill	33
VI.	How to Recognise the Paraboloid—Zonal Testing	40
VII.	Silvering—To Prepare the Mirror for Silvering —To Prepare the Bath—To Polish the Film—A Few Hints—Care of Film ...	46
VIII	The Achromatic Object Glass—Calculating Curves, First Principle—Second Principle	55
IX.	Practical. Shaping and Grinding—Polishing	63
X.	Testing and Figuring	68
XI.	Testing and Figuring	71
XII.	The Flat or Diagonal Plane—Cutting out a Plane	74
XIII.	Mounting Lenses and Mirrors	78
XIV.	Reflector Tubes	82
XV.	The Flat Cell and Suspension	88
XVI.	Stands	91
XVII.	The Observatory	96
XVIII.	The Observatory	100
XIX.	The Observatory	104
XX.	Eyepieces	107

PREFATORY NOTE.

THE ensuing chapters appeared originally as a series of articles in the *English Mechanic*, March—October, 1918. The Author desires to acknowledge gratefully his indebtedness to the Editor of that journal for many facilities accorded; to Mr. Harold Notley for drawing several of the diagrams from his rough notes; and to not a few other friends for helpful hints and suggestions.

WM. F. A. ELLISON.

Armagh, 1920.

THE AMATEUR'S TELESCOPE.

CHAPTER I.

INTRODUCTORY.

Nearly 150 years have passed since William Herschel, then the unknown organist of Bath, began those experiments in telescope construction which in a few years made him the greatest astronomer and greatest master of the telescope that the world had yet seen. The Newtonian reflector was his chosen form of instrument almost of necessity. The achromatic lens was as yet in its infancy, and the Gregorian construction was too oomplicated for an experimenting amateur, and was, besides, cnly suitable for small sizes, and consequently limited in its possibilities. A distinguished band of workers have, during the past century and a quarter, followed Herschel's lead, and nearly all have imitated his preference for the Newtonian, although the achromatic object-glass has become such a formidable rival to the concave mirror. The reason for the popularity of the Newtonian is still the same as in Herschel's day. It is the amateur's telescope, because, now, as then, it is the easiest to make and the easiest to mount, and far the cheapest either to make or to buy of any class of telescope. And, though cheap, it is not "cheap and nasty." A good mirror is to the astronomer a thing of beauty and a joy for ever, capable of unfolding all the myriad glories of the heavens and of holding its own with the most costly products of the optician's art in definition and power. The names of those who have worked on it and helped to perfect it include many of the very brightest lights of the world of science in the nineteenth century. Lord Rosse, Lassell, With, Calver, Draper, Common, Foucault, Liebig, all gave of their best brains to the problems—most fascinating and alluring problems they are—set for solution by that beautiful sphinx, the paraboloidal mirror. That simple-looking disc of glass, with its almost imperceptible curve, shows little indication of the magical and mysterious powers which lie latent in it, powers to open to the astonished gaze a universe of glory and wonder; or of the amount of thought and anxious endeavour which have gone to the perfecting of its subtle curve and the depositing of its shining skin of silver.

Briefly, the advances since Herschel's time have been:—(1) The invention of the method of depositing a film of silver on glass by Liebig, improved later by Brashear and others, which made glass possible as a material for optical specula; and (2) Foucault's lamp and knife-edge, which made it possible for the

workman to see exactly what he was doing while figuring the reflecting surface. It was unfortunate that Foucault's test was not known to With. Had it been, it would have immensely increased that great master's output, and also improved the quality of his work. As it was, Calver, though little, if at all, With's superior in skill, reaped the harvest of accuracy which With just failed to gather in. Many of With's specula have been retouched, to their great benefit, both by him and by the present writer, though one always handles a With mirror with reverence and wonders at the skill which could come so near perfection working in the dark.

Perfection—that is what the concave speculum has attained of late years. It is possible for a worker of sufficient skill and experience now to set about making a mirror, secure in the knowledge that he can produce a surface in which the most extraordinarily delicate test the human brain has ever devised can detect no flaw. Nay, more, he can produce a mirror whose accuracy is really *beyond* the requirements of telescopic vision. A mirror which has faults quite visible to the expert using Foucault's test will often perform in the telescope just as well as one which has none, because the faults of the faulty one are too small to affect the visual image. The test is, in fact, *unnecessarily* delicate. But then nothing is ever "good enough" so long as it can be improved, and no good speculum maker will let a mirror out of his hands which has a defect which he can see and can remove, however small that defect. The earnest and industrious speculum worker never really knows to what his efforts may lead him. In most trades the amateur must be content to follow humbly, and at a distance the steps of the trained professional man. In telescope-making, and especially in the making of the essential parts of the reflector, it is the other way about. The amateur has shown the way to the professional, and forced the pace for him, ever since Herschel's time. Herschel himself was an amateur, so was Lord Rosse, so was With, so were Draper, Common, Calver, Wassell, and Alvan Clark. That many of these *became* professionals only emphasises the fact that they began work as amateurs and ended by beating the professionals at their own trade. That they did so is largely due to their recognition of the principle expressed in the phrase I have just now used. "Nothing is 'good enough' so long as it can be improved."

The chapters which follow are dedicated to the amateur telescope makers of the world in the hope that some at least of them may be thereby helped on the road which led Herschel, With, Calver, and Clark from humble amateurism to the headship of the world's professional makers. The writer's first telescope was constructed when he was aged ten years, and consisted of a spectacle lens, a sixpenny microscope, and a pasteboard tube, with which humble instrument, innocent of achromatism, he first viewed Jupiter's satellites, the phases of Venus, and the lunar mountains. This was the beginning of the ladder which has already reached ~~seventy~~ mirrors of apertures from 6 to 12 inches, and object-glasses of 4, 4½, 5, ~~and~~ 5¼-in. aperature.

Literature.

The beginner who seeks for literature to direct his efforts will meet with the difficulty that most of the works on the subject of speculum making are out of print, or buried in back numbers of magazines, especially those of the *English Mechanic*. Draper's papers are only to be got at in the records of the Smithsonian Institute. The very excellent articles of Francis may possibly be obtainable in a public library in Vol. VII. of *Amateur Work*. Wassell wrote in the *English Mechanic*, 1881-3. Browning's "Plea for Reflectors" and Horne and Thornthwaite's "Hints on Reflectors" are both out of print, as is also a useful little book by W. Banks, F.R.A.S. The only thing of the kind still in print is a helpful chapter on the subject in Hasluck's "Glass Working by Heat and Abrasion," published at 1s. 6d. by Crosby Lockwood & Co.

Even if all these were obtainable they have one defect in common. They are more or less out of date. The most recent of them represents the state of progress in the art of mirror-making existing in 1890-95 or thereabouts. And if nothing else had happened since then, the invention of carborundum in 1898 was sufficient to revolutionise the whole process of grinding, and to place emery out of court as an abrasive. This material, a carbide of silicon, and manufactured much in the same manner as carbide of calcium, was first made at the Niagara Falls Electric Works, and began to come into use for glass working about 1900. In that year the writer obtained a sample in Dublin, and since then has used no other grinding material, except for the very last stage of fine grinding. Carborundum cuts about six times as fast as emery, and with No. 80 a 6-inch mirror can easily be rough-ground to curve in less than half an hour, and the whole process of grinding can be done in two and a half to three hours.

CHAPTER II.

Tools and Materials.

For the amateur, speculum-making has one great advantage: it does not require an extensive or expensive outfit of tools. Indeed the essential ones need not cost more than a very few shillings. Opticians, it is true, use cast-iron or brass tools, carefully made to gauge and ground true, for forming the curves both of lenses and specula. And where a large number of curved surfaces have to be produced, all of the same radius, these are indispensable. But for the purposes of the amateur mirror or object-glass maker glass tools are preferable, and both their cost and the trouble of making them are negligible. Here, then, is a list of the things necessary to be provided before we begin. It is neither long nor costly:—

1. A Pair of Equal Glass Discs.—One for the mirror, the other for the tool. The mirror-disc should have a thickness not less than one-eighth of its diameter—perhaps one-sixth is better still. The tool may be of lighter stuff.

2. A Barrel—or, better still, two Barrels.—Forty-gallon paraffin-oil casks are convenient and easy to obtain.

3. A Pound or Two of Pitch.—There are three kinds usually on the market—English, Russian or Archangel, and Swedish or Stockholm. Any of these will do, but Swedish is commonly preferred. As now sold, no cleaning or straining is needed. Purchasable of chemists or oil and colour shops.

4. Carborundum, No. 80, 220, FFF.—15M., 30M., and 100M. powders are suitable and sufficient. Sold in 1-lb. and 2-lb. tins. Buy from the makers*, on no account from the "local shop." or grades may be found disastrously mixed.

5. Jeweller's Rouge.—One pound will polish quite a number of mirrors. B quality optical rouge. Canning & Co. Gt Hampton St. Birmingham. is best.

The above are indispensable. To these may be added a list of articles not indispensable, but very desirable :—

a. A Lathe.—If the worker has one, he can edge up his own glass discs, thereby reducing their cost, which is about doubled if the plate-glass merchant is asked to edge them. Moreover, if the glass-shop edges them, we must put up with whatever finish comes from the shop, which is generally pretty rough. If one can edge them oneself, they can be finished as neatly as one's taste requires, though few will care to be as particular as With, who *polished* the edges of his specula. The possessor of a lathe can also turn up the blocks and handles which he requires for mounting and holding discs during working, and can do a lot of neat jobs when he comes to mount his mirror and flat. To *make* a flat a lathe is indispensable. It is very desirable that the grinding and polishing should be done in different rooms. If the worker is lucky enough, or rich enough, to possess the house-room for this, the polishing-room should be provided with its own barrel, and nothing contaminated with carborundum should on any account be allowed to enter it.

b. An Oil-stove or Gas-ring is almost indispensable for melting pitch, warming glass discs before cementing, etc. (Pitch will not stick to cold glass.)—If the worker resides out of reach of gas and uses an oil-stove, it should be of the central-draught variety, with a circular burner, and its upper works should be stout enough to support a fairly heavy weight.

c. An Assortment of Enamelled Iron Dishes and Basins will be found useful for quite a number of purposes, such as holding water and rouge, and covering tools and mirrors to keep off dust during the intervals of working. Porcelain or earthenware ones are objectionable, owing to the danger of damaging a mirror by an accidental blow against them.

EDGING.

If the worker possesses a lathe, his first job will be to turn up handles and supports for tools and mirrors out of hard wood (oak, box, or mahogany for choice). The usual way of mounting the glass tool is to cement it to a disc of wood an inch or two larger in diameter than the glass. The disc has a wide bevel, and is gripped by three large countersunk screws, the heads of which hold the bevel, as shown (Fig. 1).

* The Carborundum Co., Trafford Park, Manchester.

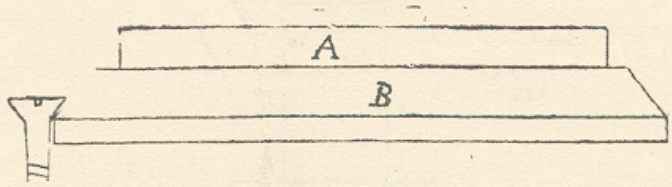


FIG. 1.—A, glass tool; B, wooden bevelled disc, and method of securing same with screws.

A preferable plan, however, is to have a thick wooden disc, considerably smaller than the glass, screwed securely and concentrically to a stout sheet-iron disc somewhat larger than the glass. The edge of this is gripped by three screws, with a small washer on the head of each. The glass tool cemented to the wood forms a sort of mushroom top. The advantage of this is that it enables us to keep the whole arrangement clean.

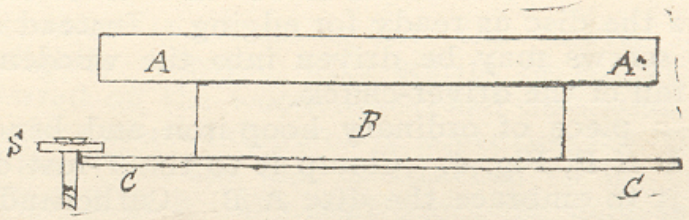


FIG. 2.—Another and cleaner way. A A, glass tool; B, thick, wooden disc; C C, sheet-iron disc; S, screw (one of 3), and washer. Drip from edge of A may be caught by sheets of thin zinc, cut to fit close to B.

Get a sheet of thin zinc, and cut a circular hole in it the size of the wooden disc. Then cut it across, dividing the hole in two. This is placed under the tool, while grinding, with the two semicircular openings closely embracing the wood disc and catches the mud and water which drips from the tool. It is removed and washed as often as may be required, and saves a lot of mess and much risk of scratches in the fine-grinding. (Fig. 2.)

It is well to have a piece of soft deal plank, nicely planed up, and cut to fit on the top of the barrel, to which it is secured with screws. To this the various discs carrying tools are screwed, and when frequent screwing and unscrewing has damaged the wood beyond repair it can be easily replaced. Three other discs, smaller than the glasses, must also be turned up. One of these, about 3 ins. diameter, is for the handle to hold the mirror. A socket is turned in the centre of it, and a cylindrical piece fitted and glued or pinned in place. A second one is similarly prepared, and has a centre-punch hollow made in its outer end to take one of the lathe centres. The third is left a plain disc, but has another centre-punch hole to take the other lathe centre. The latter two are to be used to hold the discs between centres for edging. They are cemented with pitch to the glass, and centred while still warm by placing on the lathe and rotating them, pushing them till the disc runs true.

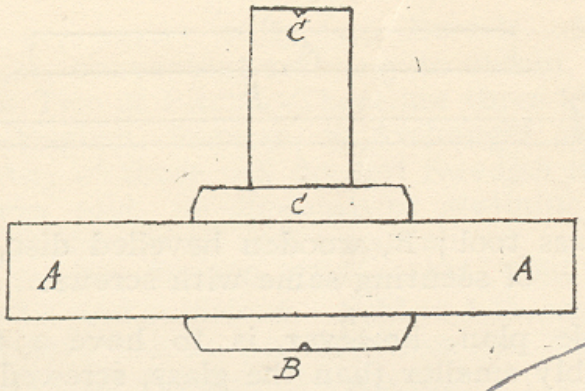


FIG. 3.—Mirror disc mounted for edging. A A, glass disc; B wooden disc; C C, second ditto, with handle. Centre-punch hollows at B and C take the lathe centres. A screw driven laterally into C serves to catch the tail of driver chuck.

Then take it off the lathe and leave on a level shelf to cool Fig. 3 shows the disc as ready for edging. Instead of a carrier one or two screws may be driven into the wooden handle to engage the tail of the driver-chuck.

Procure a piece of ordinary hoop iron and bend it to the shape of C D E F, Fig. 4. Clamp it to the T-rest of the lathe and adjust it to embrace the disc A B. Carborundum No. 80 and water are fed in at C, the iron band is tightened by a light pressure of the finger at F, while the lathe revolves in the direction of the arrow. Half an hour's work will smooth the edge of the disc, No. 80 carborundum being changed to No. 220 at the end. In this way we obtain a better and smoother finish.

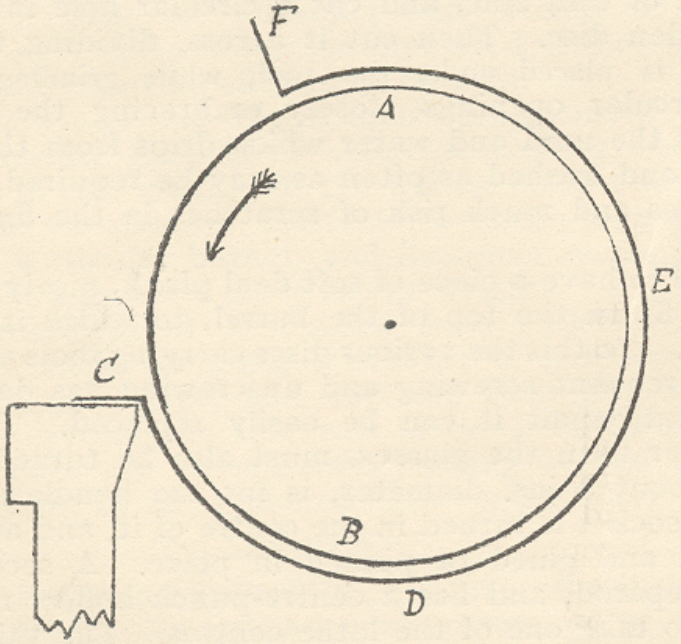


FIG. 4.—Disc as being edged in lathe. A B, glass disc, revolving in direction of arrow; C D E F, hoop iron band clamped to T rest at C. Carborundum and water are fed in at C. Drip is caught by a metal tray placed on lathe bed under D. A gap lathe will take a very large disc.

Before removing the disc from the lathe the sharp corners should be bevelled off by holding a carborundum hone to them while the disc revolves. This is a measure of safety, to avoid the danger of an ugly chip resulting from a slight accidental blow. Mirror and tool should both be edged, but the tool need not be bevelled. When edging is finished and the carbo. grit washed off, the wooden supports are detached from the glass by a smart lateral blow with a wooden mallet. Now attach the handle to the mirror and cement the tool to its wooden disc, and screw the latter to the barrel top, and we are ready to begin.

Needless to say, the above operation is not beneficial to a good lathe. If your lathe is a fine one, carborundum grit is a most undesirable neighbour. A tin tray should rest on the lathe bed to catch the droppings from the edging process, and all bearings should be covered. If the worker can obtain or rig up a common makeshift lathe for edging, so much the better.

Rough Grinding.

The next stage is roughing out the curve. The tool is warmed, slightly smeared with spirits of turpentine, melted pitch is poured on the wooden bevelled disc, and the smeared side of the glass pressed down on it, squeezing out the excess all round. When cold, the disc is attached to the barrel top as shown in Figs. 1 or 2. We next warm the back of the mirror. smear a little turps in the centre, pour sufficient melted pitch on, and press the handle firmly on. When cemented on it looks like this :—

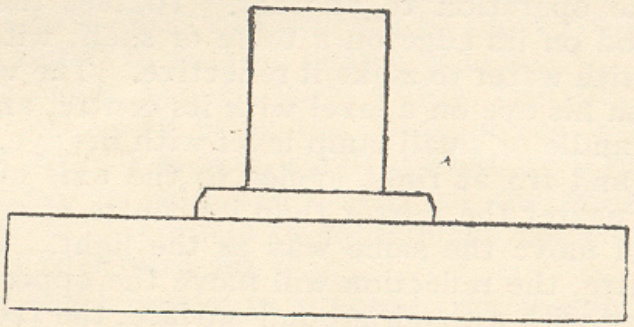


Fig. 5.—Ready for work. Mirror disc, with wooden handle attached, for grinding and polishing.

Ordinary 8 oz. cocoa tins are convenient for melting pitch in. Of this more later on, when we come to polishing. We place a basin of water and a handful of cottonwool handy on the work bench and a tin of No. 80 carborundum, strew a little carbo. on the top of the tool, dip the face of the mirror in the water, and place it on the tool.

We must now make acquaintance with the mirror maker's "three motions." In order that the desired curve may be produced, the upper disc must (1) travel to and fro across the lower, (2) rotate about its own centre, and (3) the worker must walk slowly round the barrel. It is obvious that these three motions could easily be produced by machinery, and for grinding such a machine would work admirably. But it would fail

in polishing and figuring. The labour of grinding a mirror of moderate size is not great, and hand work is all that we shall need. Motion (1) is known as the "stroke," and by lengthening or shortening it we can produce most useful modifications of the curve. In roughing out, a long stroke is useful—*i.e.*, one as long as possible, when the centre of the mirror reaches the edge of the tool at the end of each traverse. It produces an irregular curve, of greater depth in the centre; but at present this does not matter, as we are more concerned about excavating a hollow as quickly as possible than about its shape. The shape will quickly come right when we begin fine-grinding and shorten the stroke. An elliptical stroke, or "side" stroke, is useful for some purposes, but it slows the cutting.

After working for a few minutes the charge of carbo. begins to get dry; so we lift the mirror and add a few drops of water, and so go on till the feel of the grinding tells that the abrasive is ceasing to cut. We then lift off the mirror and renew the charge. The older authorities recommended washing the tool and mirror to remove the mud which has accumulated. But this is not necessary at the present stage, and wastes time and labour. When it is deemed advisable to try how deep the curve is, then we must wash the mirror free from all traces of abrasive, using for this purpose the cotton wool before mentioned. Cotton wool is used instead of the sponge once recommended, because when each stage of grinding is completed the cotton can be thrown away and a fresh, clean bunch taken for the next stage, thus avoiding all possibility of carrying over grit from one operation to another. To test the curve, the mirror is stood on its edge on a table or shelf, with its surface well swilled with water to make it reflective. The worker stands before it, with his eye on a level with its centre, and holding in one hand a candle or small lamp level with his eye. He moves the light to and fro at right angles to the axis of the mirror. If the eye is nearer the mirror than its centre of curvature, the reflection will move the same way as the light. If further off than the centre, the reflection will move the opposite way. In this way, even with a rough ground surface, the radius of curve can be ascertained within a few inches.* The further the fine-grinding proceeds the more accurate this test becomes. It is not usually necessary to be particular to a few inches about the focal length of a mirror. But sometimes it is required to work as close as possible to a given focus. In such a case the rough-grinding should stop when the radius of curve is still about 8 ins. to 1 ft. longer than is required, leaving this overplus to be brought down in the next stage. Being more finely ground, the wet surface is then capable of producing a fairly definite image of a light, and we can supplement the method above given of testing the curve as follows: Taking the testing lamp to be described in the chapter on Foucault's test, we substitute for the brass tube carrying the pinholes a tube of perforated zinc. For the knife edge we substitute a vertical piece of ground glass, and mount this and the lamp abreast on one base. By placing these in the centre of curvature of the mirror, we get

*. A spherometer is very useful here. See p. 65.

an image of the perforated zinc thrown on the ground glass. When it is focussed as sharply as possible, the distance from mirror to ground glass is the radius of the mirror's curve. A long lath marked in feet and inches is useful for measuring. It is well to remember that the radius of curve usually shortens about ½ in. in the process of polishing, and this should be allowed for if an exact focus is to be worked to. With care, it is possible to get within ¼ in. of a given focus.

Having roughed out the curve to within a little of the required depth, the next step is to cleanse away most thoroughly all traces of the coarse abrasive. The mirror is well sluiced with water, the tool and its block are detached from the barrel and sluiced under the tap, and crevices scrubbed out with a brush (an old tooth brush is excellent), and the top of the barrel is also well washed with plenty of water.

Now we replace the tool in position, throw out the water in the basin and the old cotton-wool, get a fresh handful and refill the basin with clean water. We now proceed, using 220 carbo. If the curve is very near the required depth, we shorten the stroke to one-third diameter; but if we are still several inches off the required focus it must be kept long for the present. If the curve requires no further deepening, six "wets" of 220 carbo. will suffice for this stage. (Each time a charge of carbo. is ground down and a fresh lot applied with water is called a "wet.") Five minutes is an average time for a wet; so each grade of fine-grinding will last roughly half an hour. We may here add that if a very long stroke has been used in roughing, the first effect of changing to short stroke may be to lengthen the radius of curve a couple of inches. It will, however, shorten again, though more slowly, and the effect of the short stroke will be to bring the curve of the mirror approximately to a part of a sphere, which is what we want at present. We must persevere with 220 carbo. till the desired radius is quite reached, for the effect of subsequent grades in deepening the curve will be almost nil.

When at length ready to proceed, the washing-up process is carefully repeated, and we change to F F F. Six wets each of this, of 15M., 30M., and 100M., are given, washing up with care after each grade of powder. There is no need to elutriate carborundum, as was formerly done with emery, to obtain the finest grades of all. No finer can be produced than the 100M. supplied by the makers. Indeed, it may be doubted whether this gives any finer surface than 30M. or 60M. Polishing may be commenced on a surface fined with any of these three. But we may with advantage use a sixty-minute settling from Oakey's finest washed flour emery to finish with. A pound of this emery is placed in a large glass jar, the jar is filled with water and well stirred, and then let stand for an hour, after which the liquid is drawn off with a siphon of rubber tube into another jar, care being taken not to disurb the emery at the bottom. The siphoned liquid is let stand till it deposits all the solid matter suspended in it, and this sediment is used to give the final fining to our mirror. Great care is necessary in this final

stage, and also with 100M. carbo. The quantity of abrasive between the close-fitting glass surfaces is so small that they sometimes seize each other and cling so fast together that it is difficult to separate them without a serious scratch. If the discs begin to cling, they should be slid apart at once, lest worse happen.

When the mirror is properly fine-ground it will be possible to read large print through it at some inches distance, or to obtain sharp vision of the sashes of a window at several feet. But the beginner should beware of accepting this as an infallible test of fitness for polishing, as it may consist with the presence of large pits and scratches surviving from the coarser abrasive. The best safeguard against these is to be thorough in the earlier stages of the fining. The six wets of each grade above described will be found sufficient, if care is taken to grind each down completely. Pressure on the glass is a help to the thoroughness of the grinding, and can have no ill-effect provided the thickness of the mirror is not less than the 1-6 diameter before prescribed. Some workers wash the surface of both mirror and tool with the cotton-wool after each wet, but this is not necessary, though perhaps advisable in the 30M. and 100M. stages. The writer has always made a practice of mixing the finer carbo. grades (15M. to 100M.) with alcohol, and keeping them in corked bottles. The bottle is shaken and a few drops poured out on the tool for each wet, a few drops of water being added. These powders are so clinging that it is difficult to distribute them over the tool dry, and they do not readily mix with water. Moreover, a certain gradation of fineness can be obtained by shaking the bottle vigorously for the first wet, less vigorously for the second, and so on, and very slightly for the last.

Another way of obtaining a final fine-grinding is by making a pitch-tool out of hard pitch. After 100M. is finished with, we carefully wash all up, and replace the tool on the barrel. Dry the surface with a cloth, and smear a little spirit of turpentine over it with the finger tips. Now melt some hard pitch in a tin over the oil-stove. It must be quite thoroughly melted. When completely liquefied, smear the face of the mirror thoroughly with a lather of soap and water, pour the melted pitch all over the tool, take mirror at once and press it down on the soft pitch, moving and twisting it about till the pitch is judged hard enough to retain its shape of itself. Now slide the mirror off, and you have a pitch surface of the same curve as the mirror itself. Let this cool completely, and then apply a thin layer of the 100M. carbo., mixed with alcohol, all over it. Work the mirror on this in short strokes for from ten to twenty minutes, and you get a semi-polished surface, which, if thoroughly done will polish on the rouge tool in about three hours' work instead of the usual six. This method of doing the last stage of fining has the merit of being perfectly safe, both from seizing and scratches.

It is in the last stages of fine grinding that scratches usually originate. A scratch during polishing is rare, and can only result from carelessness, such as approaching the polishing tool

with garments or person contaminated with grit, leaving the tool exposed to dust, " spring cleaning " the room when polishing is in progress, etc. (N.B.—The polishing room should *never* be swept, and no feminine hand should ever be allowed, on any pretext whatever, to " tidy " it. Total destruction of a polished surface may be the result of neglect of this rule. " Let sleeping dust lie " should ever be the mirror maker's maxim. It will do less harm on the floor than on his tools or on optical surfaces. A lock on the door and the key in his pocket is the best safeguard.) But all endeavours should be directed to securing immunity from scratches in the fine grinding. Extra care in the washing of tool and barrel and mirror, the provision of a separate basin for the final operations, and covering the work bench with sheets of clean paper will usually secure a clean surface on which to begin the polishing. Very slight scratches need not be regarded, as they will polish out. But even serious ones will often be invisible on the fine ground surface, to start into conspicuous and ugly visibility when polishing begins.

Many workers recommend the use of a pocket lens to examine the surface after each stage of the grinding, in order to ascertain whether all marks left by previous grades have been ground out. The experience of the writer is not favourable to this as a test. Even the microscope is not always able to tell whether a surface is well or ill prepared before polishing has been begun. The large deep pits and scratches are so disguised by the presence of the mass of small ones that the most experienced eye may fail to detect their presence. It is only after about half an hour's polishing that they start into disastrous prominence. The only real safeguard is to be very thorough with the last, or last two, stages of the fine grinding. Carborundum cuts so fast that 30M. or 100M. will quickly remove even quite deep pits and scratches, and if any doubt remains as to the existence of these, a double dose of 100M. will usually make sure of them. A plan which the writer has sometimes practised is to make a scratch with a diamond somewhere near the middle of the tool, deep enough to be quite certainly deeper than any possible abrasive pit. The edge of the mirror and middle of the tool are the parts which grind most slowly. Therefore, when this scratch grinds out, it may be confidently assumed that all lesser pits are gone.

For the reason just mentioned, that the edge of the mirror gets the least grinding, it is a very good plan to do the last stages of the fine grinding with the mirror face up, reversing the relative positions of mirror and tool. The " mushroom " form of support already described (Fig. 2) will facilitate this change. In this way that part of the mirror which polishes most slowly (viz., the edge) will get the most fine grinding, and the benefit will quickly become manifest when polishing begins.

CHAPTER III.

Testing; Foucault's Shadow Test.

As soon as we begin to polish we immediately require some means of ascertaining what is happening on the concave surface of the mirror, though this knowledge is not of the greatest importance until later on, when we begin the most difficult process of all, viz., the figuring. We might, indeed, go ahead with the polishing, confident that no irremediable error would develop in the curve, so long as the tool was made and used as we shall describe by and by. Once upon a time it was believed that if a figure of a mirror once became hyperbolic it could not be remedied, and all sorts of devices to avoid the "fatal hyperbola" were resorted to. As a matter of fact, a hyperbolic mirror, though less easy te remedy than some other faulty curves, presents no difficulty to a moderately expert hand, and we could, if we desired, polish away merrily till all marks of abrasion had disappeared, without any testing at all, careless which of the list of possible regular curves turned up at the end of the process. There are only two limits to this possibility: (a) the limit of human endurance, which prescribes that half an hour's polishing at one spell is enough for the worker's patience; and (b) the limit of endurance of the pitch tool, which begins to soften, from the heat produced in polishing, if one goes on much longer without letting the tool cool down. To this we may add human curiosity, which naturally desires to see how the figure is shaping. Up to the time of With, speculum makers had to work in the dark, except for tests upon stars, for which one had to wait till the sky chose to clear, and also to dismount the mirror from its handle and mount it in a telescope tube. Naturally, mirror-making under these circumstances was a slow and uncertain process. It is owing to the genius of the great Frenchman Foucault that we now have a simple and easy method by which the figure of a mirror is made actually visible to the eye, and so delicately visible that the expansion due to the heat communicated to the glass by the touch of a finger can be clearly seen.

Foucault's method consists essentially in the provision of an artificial star, in the form of an illuminated pinhole. This of course, cannot be placed at a great distance, so that the light from it will be sensibly parallel, like that of the real stars. It is therefore placed at the centre of curvature, and although the resulting appearances differ from those seen when parallel light is converged by a mirror to its principal focus, the two sets of phenomena can be connected by a simple formula.

If the pinhole be placed at the centre of curvature of a spherical mirror, it follows from optical laws that all light from the pinhole falling on the mirror will be reflected back exactly to the pinhole again, and will form an image of the pinhole, the same size as the pinhole, on the pinhole. In this position it could not be examined. We therefore slide the lamp a few inches to the left,* causing the image to move the same distance to the right, where it can either be examined by an eyepiece or received direct into the eye. Both methods are useful. If

* I cannot imagine why so many workers reverse this. Surely the right hand is the proper member to manage the very delicate movements called for in the knife-edge

the image be allowed to enter the eye, the mirror is seen full of light, like a full moon. Now comes in the second part of Foucault's ingenious plan.

A vertical knife-edge is mounted so that it can be made to slide laterally across the path of the pencil of light, close to the point where it focusses just before entering the eye. When this is done the eye sees the shadow of the knife-edge cross the

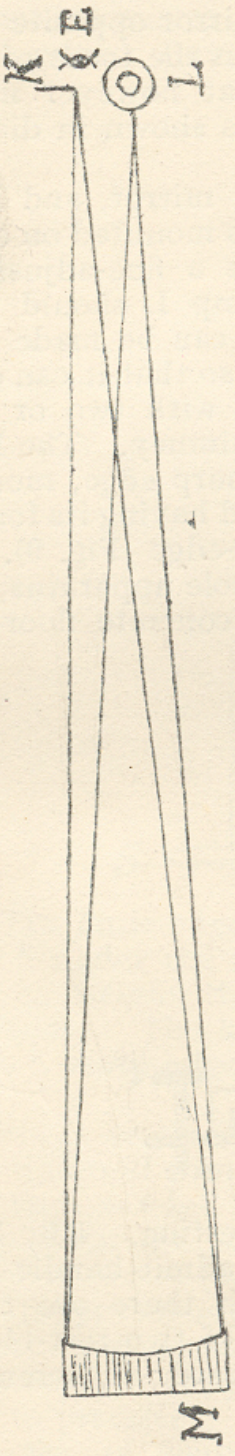


FIG. 6.—Diagram of Foucault's test. M, mirror; L, lamp; K, knife-edge; E, position of eye.

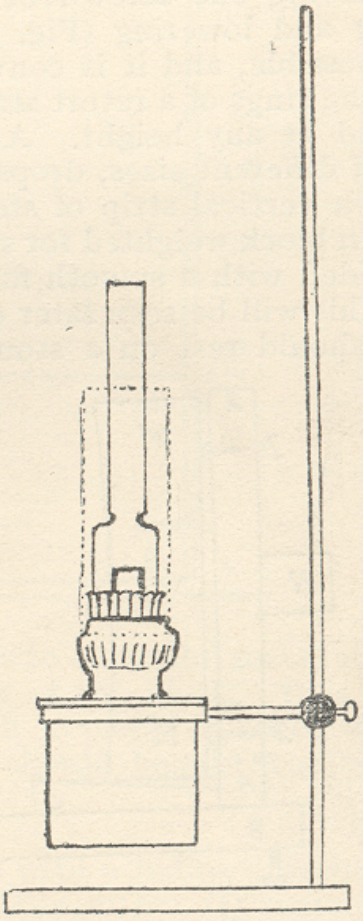


FIG. 7.—The Lamp and its Stand. The dotted lines show the tube carrying the pinholes when placed over the chimney.

mirror. Hence the name "shadow test." But the manner of its crossing differs according to the position of the knife-edge with respect to the focus. If it cuts the beam within (nearer the mirror than) the focus a vertical shadow crosses the bright

face of the mirror the same way that the knife-edge moved. If it is *outside* the focus, the shadow crosses the opposite way, If it be exactly *at* the focus, the surface of the mirror darkens all over evenly, and looks flat, no moving shadow being seen either way. These are the appearances characteristic of a sphere. But if the mirror is not spherical, but has some parts of a greater and some of a lesser radius, however small the difference, what will happen? Obviously we shall see the shadow broken up into parts crossing the mirror opposite ways, if the knife-edge is so placed as to be within the focus of some parts and outside that of others—and that however minute the difference may be. The arrangement is shown in diagram Fig. 6.

K is the knife-edge, L the lamp, M the mirror, and E the position of the eye. In practice the mirror is mounted on a kind of easel having one screw-foot in front, as a fine-adjustment for raising and lowering (Fig. 8). The lamp L should be as small as possible, and it is convenient if it can be made to sit in one of the rings of a retort stand (Fig. 7), so that it can easily be clamped at any height. A brass tube, with two or three pinholes of different sizes, drops over the chimney. The knife-edge K is a vertical strip of steel with a sharp edge, mounted in a wooden block weighted for steadiness and having its forward edge provided with a smooth metal straight-edge (Fig. 9). The object of this will be seen later on. The whole apparatus, with its table, should rest on a stone, tiled, or concrete floor—not

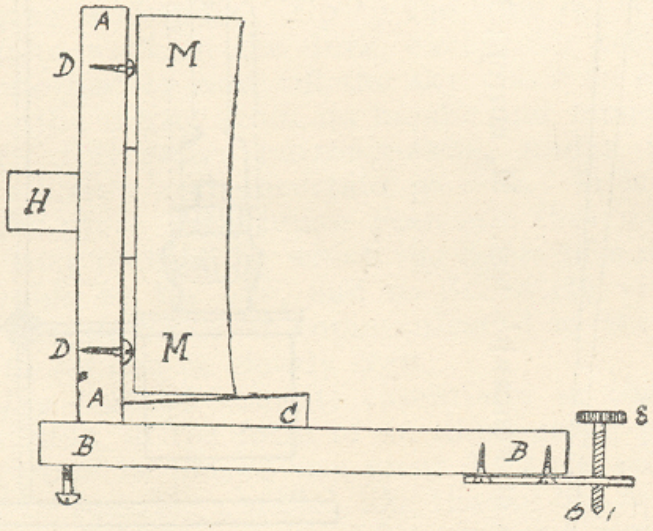


FIG. 8.—Easel for carrying mirror when testing. BB, base-board; AA, upright, divided in two to admit handle H of mirror MM; screw-heads DD, of which there are three, form a rest for back of mirror; C, one of two rest-blocks, inclined, to prevent mirror tilting forward; S, screw for fine inclining movement.

boarded. If this is not attainable, then let the mirror easel rest on a bracket bolted to the wall, and the table carrying the lamp be of the stoutest make, and stand on a hearthstone or some similar spot. The quantities which the apparatus is

designed to measure being of the order of millionths of an inch, no movement of the apparatus itself is tolerable. A convenient form of support for the lamp and knife-edge is a very stout tripod table, with a small top made of soft pine board, planed nicely smooth. Its height should be such that a man kneeling at it can easily rest his elbows on it. It is advisable for the worker to make his own.

We have already seen what are the appearances presented by a spherical mirror when put to the question by the pinhole and knife-edge. But we shall rarely see a truly spherical one.

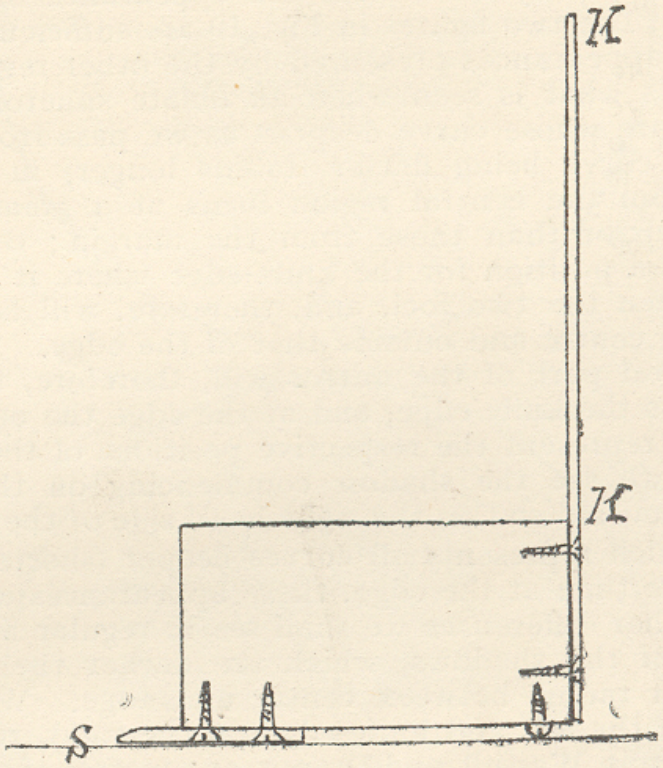


FIG. 9.—The knife-edge. Side view to show the metal straight-edge S under the forward edge of the block. It is a good plan to weight the block with a piece of sheet lead for steadiness. The knife-edge K should be stiff, but bevelled off to a sharp edge.

Nearly always we shall have curves with a radius differing more or less in different parts. They will be either (1) radius longer in centre than at edge (oblate spheroid), (2) radius very slightly shorter in centre (ellipse or prolate spheroid), (3) radius a little shorter still in centre (paraboloid) or (4) radius very much shorter in centre (hyperboloid). Of these, (1) and (2), as well as the sphere, are under-corrected ; (4) is over-corrected, and (3), the paraboloid, is truly corrected, and this is the curve which we desire to produce.

There are, of course, besides these an infinite variety of irregular figures, which may be combinations of any two or more of the above, or figures not symmetrical, such as astigmatic curves produced by " flexure " (strain, or bending of the glass). The last is not likely to be met with if good glass of proper thick-

ness is used and the directions already given as to mounting and holding it are followed. But if a disc of glass be cemented to a stout wooden block covering the whole of its back, as we have known some beginners do, it is pretty certain to be flexured; and a flexured mirror is rarely curable. The most usual irregularities are hills or hollows in the centre, rings, and "turned-down edge." For the present it will only be necessary to be able to recognise the appearances presented by the principal types of regular figure, viz., oblate spheroid, sphere, paraboloid, and hyperboloid.

We have already dealt with the appearance of the sphere under test. The two figures in Fig. 10 are sufficient to give an idea of the appearances presented by the other regular figures. I represents what is seen when an oblate spheroid is tested, *i.e.*, any figure whose curve deepens as we pass from centre to edge. The curve being flatter (radius longer) in the centre, the rays from the central region focus at a greater distance from the mirror than those from the margin; consequently, we can find a position for the knife-edge where it will cut the beam between the two foci, and, therefore, will be inside the focus of the centre and outside that of the edge. The shadow at the central part of the mirror will, therefore, traverse the same way as the knife-edge, and at the edge the opposite way. If K and L represent the respective positions of the knife-edge and lamp, we see the shadow commencing on the left-hand edge of the mirror and on the right-hand side of the centre.

In 2, which represents all curves deeper (shorter in radius) at the centre than at the edge, these appearances are reversed. The only other differences we shall see in regular figures are in the depth of the shadows, which are darker the greater the difference in radius between centre and edge. We have put the lamp on the left and knife-edge on the right, reversing the order of Francis, Wassell, and Draper, as a matter of convenience. It is most important that the knife-edge should be next the observer's right hand, as very delicate movements of it have to be controlled. The lamp is never moved when testing. A little practice and thought on the cause of these phénomena will enable the beginner to distinguish a hill on his mirror from a hollow, even if the nature of the irregularity is not obvious at first sight.

The lamp used in these tests may be any small-flame one. A small Argand burner, with a narrow chimney, is perhaps the best. The smaller the source of light the nearer the knife-edge can approach the pinhole, and the less will be the *ecart* needed of pinhole and knife-edge from the actual optical axis of the mirror. They should not be too far from the axis, or distortion of the shadows will result; and, contrary to the opinion of many workers, the pinholes should not be too small. It is convenient to have two—one of liberal size, pierced with an ordinary sewing-needle, for rough-testing, and a small one, made with the point of a very fine needle, for fine work, eyepiece testing, and testing a mirror after silvering. We have known grotesque errors result from using too fine a hole. Indeed, on

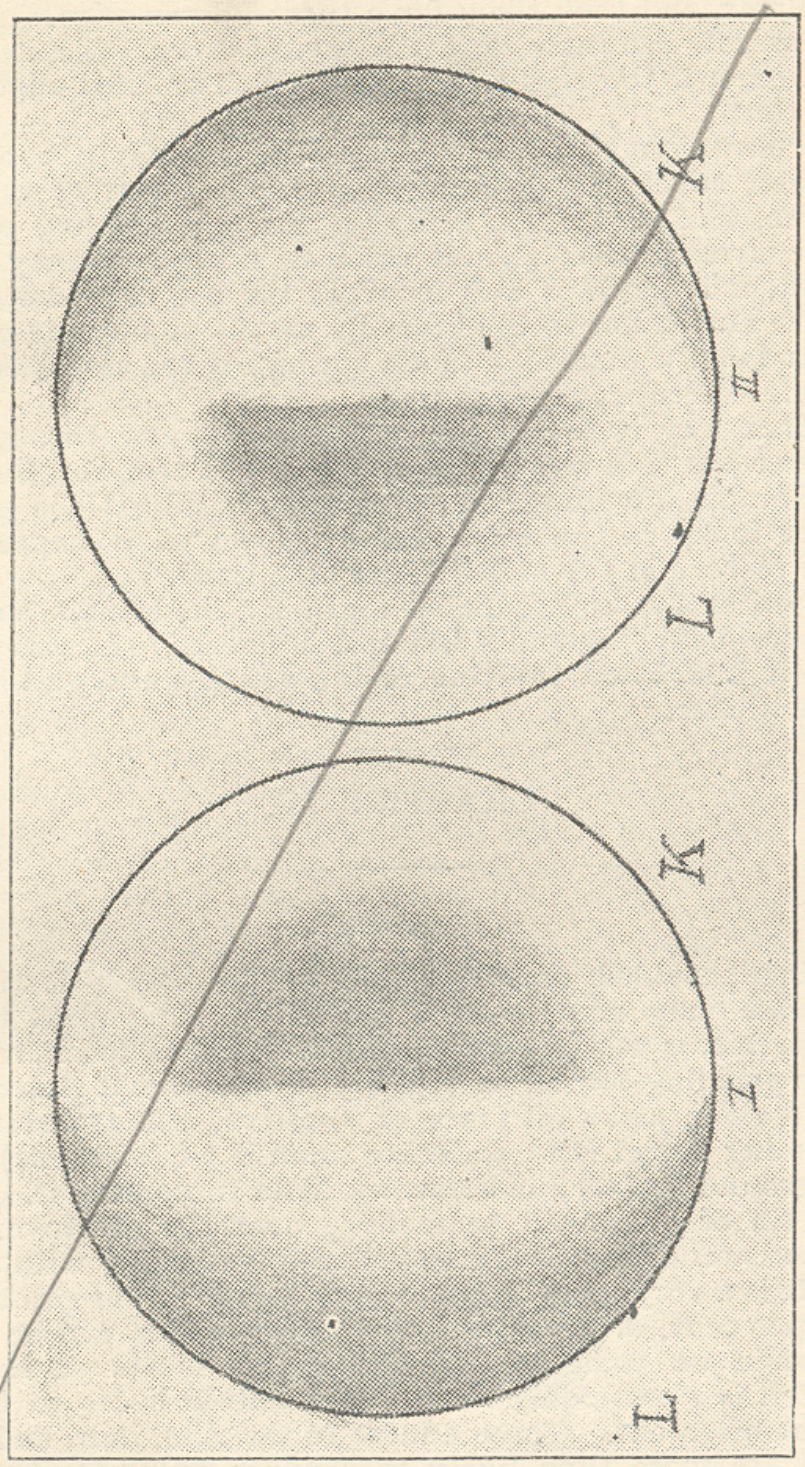


FIG. 10.—Under-corrected (I) and over-corrected (II) shadows. L and K are the positions of lamp and knife-edge respectively. Paraboloidal shadows differ from II in depth of shade only. I, inner shadow, is moving towards L; outer towards K; II, *vice-versa*.

one occasion an absolutely perfect mirror was sent to the writer to correct for a "turned-down edge," which was entirely non-existent except in the owner's testing apparatus. He used an acetylene flame and an excessively tiny pinhole, with the result that he saw a series of diffraction bands inside the margin

of his mirror, and took them for a turned-down edge. An eye-piece test will instantly detect a turned-down edge if any be present, even if too slight to notice with the knife-edge. But of this later.

It is convenient to cut two openings in our brass tube, opposite each other, cover the whole with a sliding collar of very thin sheet zinc, and pierce the holes in this, one in each opening. Lest the arrangement should collapse if the chimney should over-heat, it is perhaps well to avoid the use of solder, and to secure the zinc collar to the brass by means of a spring clip. A piece cut from a discarded clock spring, of the requisite curve to encircle the tube, answers well.

Another way is to file the brass tube nearly through, and then pierce the thin remaining metal with a needle. But there is considerable advantage in being able to adjust the pinholes higher or lower in the tube, which, of course is impossible if they are pierced in the metal of the tube itself.

The writer's lamp has an oil-container made of a small tin which once held "Brand's Chicken Extract." It was chosen because it just fitted the ring of the retort-stand and because of its small size.

CHAPTER IV.

Polishing.

Having provided ourselves with a Foucault's testing apparatus, we may now proceed to polish. The glass tool on which the mirror was ground is, with its wooden block, removed from the grinding barrel, thoroughly scrubbed and sluiced with water, to clean away all trace of abrasive, and transferred to the polishing barrel (and polishing room if we have one). Dry its fine-ground surface, and smear a little turps over it. Meanwhile a tin of pitch will be melting over the oil-stove. This should be carefully watched, and stirred frequently with a short stick. It is a very great improvement to add to the pitch about 5 to 10 per cent. of beeswax. The effect of this will be appreciated when we come to cutting out the facets on the tool. Pure pitch is abominably sticky, and also is liable to fly into tiny chips when cut. These adhere to the skin, hair, and clothing, and are more than likely to conduce to profanity, being very difficult to get rid of. The wax-pitch mixture does not chip, and its stickiness is so much reduced that it can be moulded with the fingers when soft without adhering. Still more important is what may be called its "flexibility," using the word in the motor-engineer's sense. Pure pitch, to work well, requires to be very close to the ideal degree of hardness. If it is too soft it very rapidly produces a deep hyperbola, and also a "turned edge," the dread of all the old mirror-makers. If too hard it scratches. But the wax-pitch mixture will work well, within much wider limits of hardness, and seldom produces a turned edge. It should be just possible to mark it with the

thumb-nail when cold. Watch that the pitch does not boil, and if it shows signs of doing so, lower the lamp. Prolonged heating hardens it. To soften, add carefully a little spirits of turpentine. (Do not spill any over the lamp, or there may be an explosion.) Not more than a teaspoonful should be added at once, as its effect is quite disproportionate to its quantity.

While the pitch is melting we get the mirror ready by standing it face up and painting it all over with a thin paste of rouge and water. We will require two or three glass jars (such as 1-lb. jam jars) and a plate of glass to cover each to exclude dust, a camel's-hair brush, large and flat, and a knife, or, better still, an old razor. We also need a stamping tool. To make this, take a piece of nice cleanly-planed wood with straight faces, about 9 in. x $1\frac{1}{4}$ in. x 2 in. Cut two pieces of thin hoop-iron 9 in. long, and file one edge of each to a wedge-shape. Clean both pieces up well with a file, drill three or four holes in each, and screw them to the sides of the piece of wood, so that their sharpened edges are parallel and $1\frac{1}{4}$ in. apart. This is our stamp for marking out the facets of the tool. In section it is like illustration below figure 11.

Mix in one of the jam-jars a tablespoonful of rouge with water to a thin cream, and paint some of it over the face of the mirror with the camel's-hair brush. When the pitch is quite liquid all through grasp the tin with a cloth, and pour it out rapidly on the tool, beginning at the edge, going inwards with a spiral motion, and ending at the centre, where a considerable excess may be poured. Lay the tin aside and at once take the mirror and press it face down on the semi-fluid mass, twisting it round and moving it to and fro for several minutes, or till the pitch is cool enough to retain its shape. It will over-

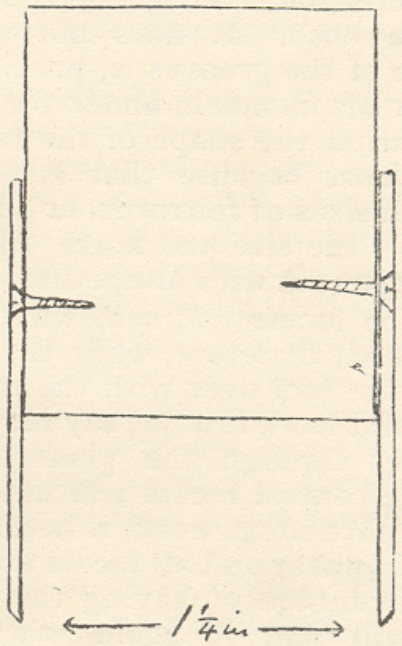


FIG. 11.—The stamp for marking facets. For small sizes the grooves may be left as this tool makes them, and need not be cut out.

flow all round the tool. Let it stay there. It will do no harm and will safely imprison any bits of loose grit that may be present. The layer of pitch on the face of the tool should be about ¼ in. deep, not more. When it is judged time, slide the mirror off, lay it aside, and take your stamp and press it lightly on the still soft tool. It leaves the impression of its two parallel edges. Lift it and place the second edge in the furrow of the first and press again. When you have gone across from side to side repeat the operation at right angles. The tool is now covered with systems of parallel lines, the two sets being at right angles to each other and dividing the surface into squares of 1¼ inch side. Now we take the old razor and proceed to cut out V-shaped channels about ⅛ in. wide along these lines. Cutting down to the glass, the strips ~~cut out~~ can be lifted clean out, leaving clear V-shaped furrows. We could not do this with pure pitch. We also get a criterion of the hardness. If the strips cut and lift out without either elongating or breaking up into bits, the hardness is just about right. A strip when cold should bend just a little before breaking. If it will bend nearly double without breaking it is too soft. But there is one point about the facets which we have not mentioned, and it is an important one. The centre of the tool must not be near the middle of a facet, nor must it be in a channel. It should be *in the corner* of a facet. If not, the mirror will polish in rings. The tool when finished should look like Fig. 12.

Note the position of the centre. It is a good plan to mark the centre with a pair of compasses before using the stamp and then to stamp the lines embracing the centre first.

The older workers, and especially Wassell, were very particular about the *shape* of the V-grooves, that the slope of the sides should be exactly 45°. This, like too many of the older refinements, is pure bosh. It does not matter in the very least what the shape of the grooves is, provided they are hollow enough to give clear air channels under the face of the mirror. Nor does it matter what the shape of the facets is either. We only make them *square* because that is easiest. The 1¼ in. squares will do for all sizes of mirror from 6 in. to 10 in. Above 10 in. we may double the size and make them 2½ in. Below 6 in. they may be dispensed with altogether.

The cutting of the facets will somewhat disturb the curve. As soon as it is finished, therefore, while the pitch is still a little soft, we must paint the tool over with the rouge and water, and place the mirror on and work it a bit, say for five to ten minutes, meanwhile observing through the glass what is happening. Probably at first the central facets will not be entirely in contact with the glass. We must work, if necessary with pressure, till all air bubbles disappear and all facets are in contact. And here we find the advantage of having the back of the mirror transparent. We will find it again when silvering. Many makers grind the back: a foolish and a totally unnecessary proceeding. The only possible object of it is to prevent light which passes through the silver film from being reflected from the back to illuminate the field of view. I have elsewhere

shown that the maximum possible amount of light so returned could not exceed that of a 12th mag. star distributed over the entire field. So do not grind the back, and both figuring and silvering will benefit. Now, having the tool in order, we proceed to polish. The motions are just the same as in fine-grinding. But now we must time ourselves. It is by time that we judge how much polishing the mirror has had. So a clock forms part of the furniture of the polishing-room. Another

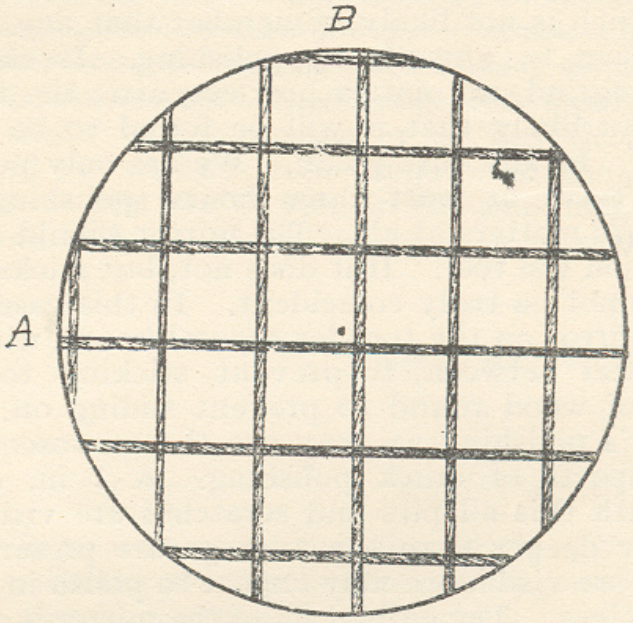


FIG. 12.—A normal pitch tool for a $6\frac{1}{2}$ in. mirror. Note the position of the centre. With the $1\frac{1}{4}$ in. stamp and a tool whose diameter is *not a multiple* of $1\frac{1}{4}$ in., the stamping may begin at the edge at A and B, and be carried right across, and centre will come right automatically.

useful article is a thermometer, which should be hung not against the wall, but freely out in the room. A rise or fall of even 5° in temperature will greatly affect the behaviour of the tool. A rise softens the pitch and a fall hardens it; consequently, a change of temperature may quite alter the character and effect of our tool. For this reason, as well as for another, to be explained later on, a light building of wood or iron is totally unsuited for a polishing place. The best place of all is a cellar or basement below ground, where the temperature will remain reasonably constant. In any case it must be a building with substantial stone walls. And the sun should not be allowed to shine in if it has a large window. Especially it must not on any account shine on the tool, or we may have to remake the latter.

Having fully taken in these *caveats*, we may begin our first spell of polishing, and go on for half an hour by the clock, using short strokes, and only stopping occasionally to renew the rouge and water. A dish of clean water, with a short stich having a large handful of cottonwool tied round one end, in it, will be found useful on the work-bench. This is to wash the

rouge off the mirror when we stop to test, and keep our hands out of the mess. We also will need a few pieces of old linen, quite clean, for wiping the optical surface dry. It is well to keep a written record of the spells of polishing and of the figure found at the end of each. At the end of the first spell the mirror should be semi-polished all over, rather more in the centre. We may possibly find a very eccentric figure at this stage; perhaps a very exaggerated hyperbola. But do not mind. Go on, and it will come to reason later on. And if it does not, but gets worse, which is not likely, remember that any figure made by polishing can be unmade by polishing. It can never be necessary to regrind, no matter how eccentric the figure. But it is more than likely that it will be found to be somewhere near a sphere. In any case go on. We are only polishing, not figuring, and have at least three hours' polishing before us before the figure matters at all. The mirror should work easily. and smoothly on the tool. If it does not, but sticks and clings, the curves cannot be truly coincident. In this case it is useful to leave the mirror on the tool for several hours,* with plenty of rouge and water between, to prevent sticking together, and three blocks of wood round to prevent sliding off. After the first half-hour's polishing we may use the microscope to ascertain the prospects of quick polishing. A 1 in. objective is suitable. With this all pits and scratches are visible, and we can see if any deeper than the average are present. If none but the finest are visible we may expect to polish in about three hours, or even less. The outer $\frac{1}{2}$ in. of the mirror is all that need be examined, as this zone is always the slowest in polishing. If the successive stages of fine-grinding have not been done with sufficient thoroughness it will be quite easy with the microscope to identify the pits due to the successive grades of abrasive. Moreover, the appearance of emery pits is quite different from those due to carborundum. The latter are sharp-edged tiny holes, deeper than they are wide; those from emery are much more diffused, and naturally polish out quicker. Hence the advantage of an emery finish to the fine grinding.

We shadow-test, just for curiosity, before going on, for it is little likely that any errors gross enough to require a change of tool will be seen. Then we proceed to another half-hour's spell, and so on till the surface begins to look well polished to the naked eye.

During the preliminary polishing the water in the dish will be getting more and more stained with rouge. When it is no longer able to cleanse the mirror set the dish aside and take a clean one and a fresh lot of water. After the first dish has stood for twenty-four hours its charge of rouge will have settled. Pour off most of the water and with what is left rinse the dish round well, and pour off all but the last few drops into a clean 1-lb. glass jam jar, and put it aside covered with a glass plate. This will give us a reserve of extra-fine rouge for the final stages of figuring. This may be repeated as often as the water in the dish becomes too deeply stained to cleanse, and the fine rouge settled from the rinsings is most important in obtaining a surface

* Called "cold pressing". A most important help.

clear of the tiny scratches rouge is apt to make. Some samples of rouge are very scratchy, and cannot be used at all without treatment. They may be stirred up in a jar of water and poured off after ¼ to ½ minute's settling. But a better plan is to make the rouge into a paste with water and then ladle the paste by spoonfuls into a flannel bag. Place this bag when full in a jar of water and knead it well under water. The fine powder comes through the bag and all coarse particles are left inside. It is a messy job, but worth while. ~~John J. Griffin & Son, Kingsway, W.C., will supply you with rouge which can usually be depended upon as fine enough for most work. Indeed, the speculum-worker cannot do better than order all the chemicals he needs (carborundum and emery excepted) from this firm.~~ B quality optica rouge n carbone o ations unneces

When we can no longer see any defect of polish with the naked eye we once more inquire of the microscope, and if no abrasive pits can be seen in the marginal zone of the mirror all is well so far as the polishing is concerned.

See p. 14.

CHAPTER V.

FIGURING.

We now come to the *crux* of the whole process. Grinding and polishing are purely mechanical processes, which any handy man should be capable of learning in a few lessons. But the man who can produce a perfectly true paraboloidal curve right up to the edge of a mirror is not a mechanic, but an artist; and the artist is born, not made. Volumes might be written on the art of figuring, and the reader of them would be no nearer being able to produce a true curve after reading them than before, if the talent were not born in him. Much depends on the figure which we find present at the completion of polishing. If it is a sphere, or an oblate spheroid, of a moderate amount of oblateness, and with no complications, such as turned down edge, we may go ahead with the tool we have been using, taking to the fine rouge collected as described already. We have merely to deepen the curve very slightly towards the centre. There are several ways of doing this. We may classify them :—

1. Parabolising by long stroke.
2. Parabolising by graduating facets.
3. The small polisher system.
4. Parabolising by overhang.

The first two are old methods, and are described in all articles on the subject, from Herschel to Wassell, and later.

(1) We have been polishing in short strokes of about one-third diameter, and straight (centre over centre). If we now increase the *length* of stroke to one-half, two-thirds, or whole diameter, we shall get a more or less rapid hollowing of the central region of the mirror. If there were no complications

to this method, parabolising would be easy ; but, unfortunately, long stroke very often means producing a turned edge. It must, therefore, be used sparingly, and with discrimination. Supposing, for example, that the figure we have to parabolise is a sphere with a turned-*up* edge, we may use long stroke for a while, being careful not to overdo it. Dealing with an oblate spheroid in the same condition, we might use it a bit more freely. Resort must be had to Foucault's test at frequent intervals. But where there is a question of a turned-*down* edge we require a control on Foucault's test. Very few mirror-workers are capable of detecting a turned edge by Foucault's test alone unless the turn-over is very gross. But an *eyepiece* test will decide the matter at once. For this we require an eyepiece of about one inch equivalent focus and a fitment to hold it which will stand in another ring of the retort-stand which carries our pinhole-lamp. To use it we simply remove the knife-edge out of the way, and slide the ring carrying the eyepiece down into its place till we can see in the latter the image of the pinhole. If the figure of the mirror is near a sphere the image will be nicely sharp. Now slide the whole stand, lamp, eyepiece and all, alternately nearer to, and further from, the mirror, so that we get the image out of focus. If the image, when some distance inside focus, is a circular disc, with a clean, well-defined edge, the curve of the mirror is true to the very edge. But if the disc has a hairy, fuzzy, and ill-defined outline, the edge of the mirror has a flatter curve than the rest ; in fact, it is "turned down." This test is infallible and extremely delicate for this one defect.

The expanded disc, outside focus, is *always* sharp in outline. Even when the mirror has a turned-up edge the appearance is not reversed, as we might suppose. In this case the outside-focus disc will have a slightly softer outline than usual, while the inside-focus one will be very sharp. In using this test, however, we must remember that the paraboloid which we are trying to produce is a figure which becomes flatter towards the edge. Therefore, we must not aim at getting the inside-focus disc too sharp. It should be just a little softer in outline than the outside-focus one when the mirror is finished. But a hairy edge to it cannot be tolerated. The turned-down edge is the mirror-maker's *bête noire*. Formerly it was considered impossible to escape it, and older makers used as a matter of course to grind off the outer half-inch, or advise stopping the mirror down. But we know better now. As the "fatal hyperboloid" is now no longer incurable, neither is the almost equally dreaded turned-down edge.

(2) Parabolising by Graduating Facets.

This is the standard method of bringing an oblate spheroid or a sphere to a paraboloid. It seems obvious that if we reduce the size of the facets of our tool, progressively from centre to edge, by widening the channels between them, we shall increase the amount of abrasion in the central parts relative to that

near the edge, and thus will obtain the desired result of a deepened curve near the centre, without increasing the stroke or imperilling the curve of the edge. The alteration will be made as shown in the figure (Fig. 13).

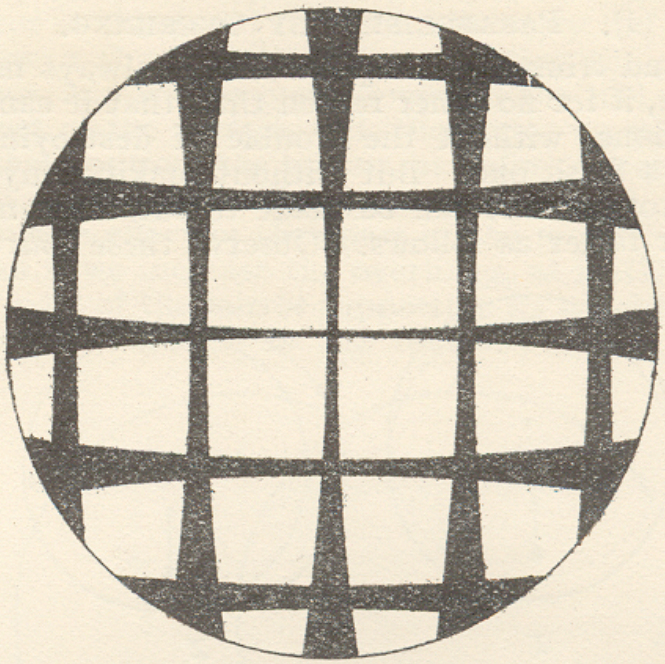


FIG. 13.—Tool graduated for parabolising. By an error of the draughtsman who copied the rough sketch, the lines are shown crossing at the centre. As before explained, the centre of tool should be situated *eccentrically* with respect to the facets. If these are disposed symmetrically about the centre, there is danger of rings forming on the mirror.

This is, perhaps, the easiest method of graduation. It might also be done by leaving the middle facet as it is, trimming off the corners of the three nearest to it, and cutting those next in order down to circles, and yet smaller circles. This will often produce the desired effect, but not always. It is well to use a broad chisel and light wooden mallet for trimming facets, and keep a large, soft brush handy for sweeping the tool free of chips. This should be kept in a dust-proof receptacle.

The above two methods of parabolising are standard methods of all the old masters of the mirror-working art. Those that follow are the result of experiments of the present writer.

(3.) THE SMALL POLISHER SYSTEM.

It has always been laid down as axiomatic that mirror and tool must be the same diameter; but, like many axioms of the old workers, this principle has no other foundation than their fear of attempting new methods. It is quite easy to both grind and polish on tools considerably smaller than the mirror. And what we have called the "Small Polisher System" is often useful as a remedy for the great enemy, "turned edge." A polisher a little less in diameter than the mirror, of hard pitch, used with short, straight strokes, will often remove a turned

edge when everything else has failed, A polisher considerably less than the mirror, even so far as only two-thirds diameter, will rapidly hollow an obstinate oblate spheroid. Naturally, this requires to be used with caution, stopping every few minutes to test, lest a deep hyperbola result.

(4). PARABOLISING BY OVERHANG.

Cutting and trimming the pitch tool is always more or less objectionable, if for no other reason than that it cannot be undone, once done, without the trouble of destroying the tool and making a fresh one. But without making any alteration in a satisfactory tool it can be made to cut the central region of the mirror faster as follows. Observe these four positions :

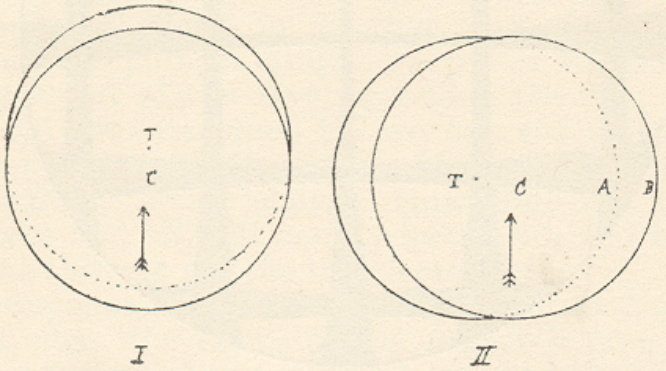
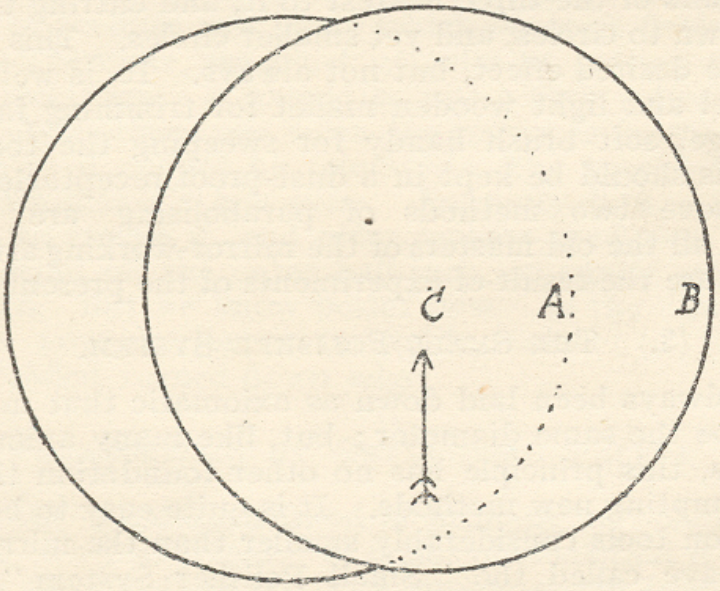


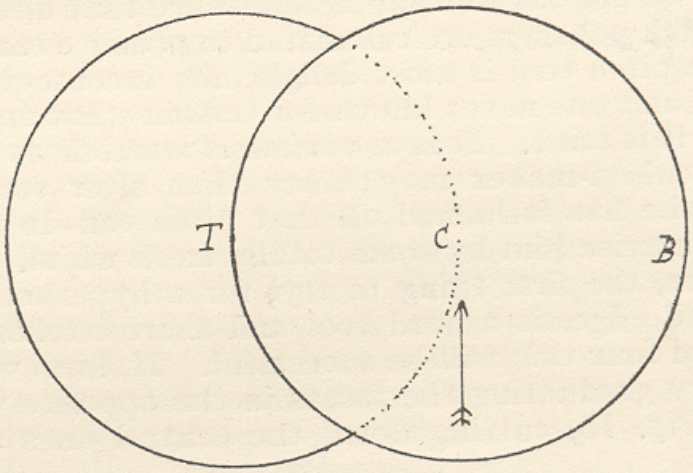
FIG. 14.—In each of the four diagrams the complete circle represents the mirror, and the arrow the direction in which its centre C is moving to and fro. T is the centre of the tool.—I., C passes over T each stroke. II., III., and IV., C passes at greater and greater distances to the right of T, according to the effect required. IV., centre of mirror works on edge of tool. Not to be recommended unless central hill is to be removed, and then very cautiously.



III.

I. Shows the ordinary centre over centre stroke, with

which we have been working. When the centres coincide, of mirror and tool, the weight of the mirror is equally supported all over by the tool. But if instead of letting the centre of the mirror pass over the centre of the tool at each stroke, we bring the mirror a little to one side, as in II., so that the crescent AB of the mirror is always off the tool, obviously the region of the mirror between C and A will be supporting the whole weight of the mirror, and will be pressed against the tool more forcibly than the rest of the surface. If, therefore, we polish with the mirror in this position, the mirror, as before, rotating about its centre, and the worker walking round the barrel, we will get a greater abrasive effect in that part of the mirror, whose radius is CA. And if we increase the overhang, as in III., we further narrow the part of the mirror supporting its weight, and further concentrate the abrasion in the central region. While if we



IV,

place the mirror as in IV., with its centre on the circumference of the tool, we get the whole pressure, due to the weight of the mirror, supported on its centre alone. To work in this position would rapidly produce a deep hollow just in the centre. It is therefore useful for removing a central hill.

We have, therefore, in this method of "overhang" (so called because the mirror always overhangs the tool by a certain amount laterally during the entire stroke) a most valuable means of controlling the figure. It is obvious that we can work the overhang method with an elliptical or circular as well as with a straight stroke, and also that we can alternately increase and diminish the amount of overhang as we work. In this way we can distribute the extra abrasion due to overhang almost *ad libitum* over any required area about the centre of the mirror, and therefore can probably produce a paraboloidal curve more easily by this method than by any other. In all these operations it is well to have the back of the mirror protected from the heat of the hands by some non-conducting material. Otherwise a good deal of trouble may result, and the success of figuring may be considerably retarded. A piece of thick pasteboard cut to a circle the size of the mirror, and with the centre cut out to admit the handle, will be found useful.

Working Uphill.

So far we have been trying to bring the figure of our mirror from sphere to parabola, or from oblate spheroid to parabola, via sphere. Now this is the way that the figure of a mirror, if left to itself during polishing, will travel nine times out of ten. We therefore call it working "downhill." But, supposing we have, to begin with, a more or less hyperboloidal figure, or that we have, in bringing the figure downhill by any of the above methods, overshot the mark, as very often happens, and obtained a hyperboloid, we will have to find means to make the curve retrace its steps. As this is considerably more difficult (it used to be counted impossible, hence the term "fatal hyperboloid"), we may call it "working uphill."

To begin with, we may lay down the principle that a hard polisher pulls the figure uphill, whereas a soft one lets it downhill. But we may as well say here at once that altough various types of pitch polishers are calculated to produce certain definite effects, the pitch tool is most delightfully inconsequential in its behaviour, and one never knows for certain what any given tool will do till it is tried. It is as *varium et mutabile* as any woman, and a speculum-maker may fancy that after some years of experience he has fathomed all that pitch can do when it will suddenly surprise him by some totally fresh whim.

However, the first thing to try, for a hyperbola as well as for a turned edge, is a hard tool and short strokes, and three times out of four this will be successful. If, however, it is not, we must try graduating the facets in the opposite way to that shown in Fig. 13, cutting down the central ones and leaving

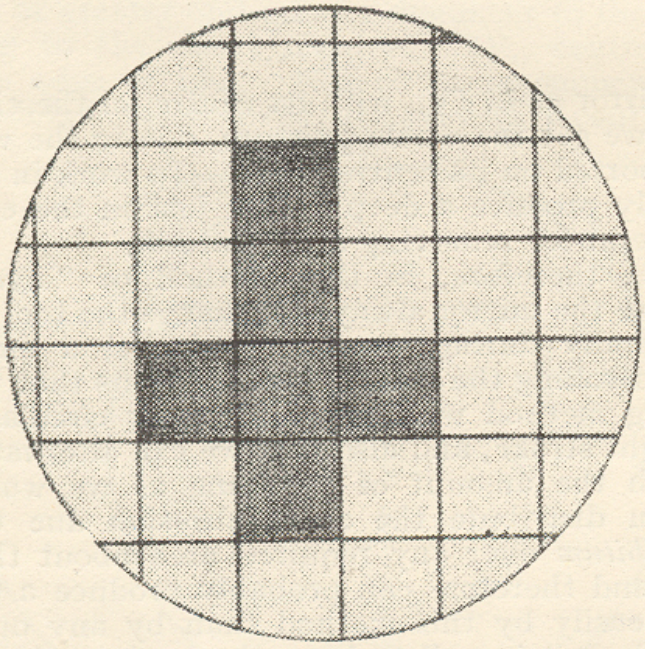


Fig. 15.—Useful for reducing a hyperbolic figure.

the marginal ones full size. In extreme cases of a very deep or obstinate hyperbola the whole centre of the tool may be removed bodily, leaving only a ring of pitch. This will probably result in an irregular oblate spheroid, whereupon we make a fresh tool, and proceed to work downhill again.

A shape which the writer often finds useful to bring a hyperbola to reason is an ordinary tool having a wide, rectangular strip the breadth of one, or even two, facets, removed right across the centre, or having two such strips, one longer than the other, crossing each other, as shown in the ensuing figure. It must not be supposed, of course, that this arrangement will produce a regular figure. It will probably result in a large hump in the centre. When the centre is sufficiently raised we can then make an ordinary "down-hill" tool, and work towards a paraboloid again as before. If we have got, as sometimes happens, a figure, which is not exactly a hyperbola but has a big hollow in the centre, the above tool, carefully used, may, with luck, bring it just right.

It sometimes happens that a ring, either raised or depressed, appears on the mirror. A polisher which rings the mirror probably has its centre in the wrong place with respect to the facets. The ringing action may be reduced, or even entirely suppressed, by using an elliptical stroke, or "side," as it is sometimes called. "Side" tends to turn the edge, though not to the same extent as long stroke, and therefore should be used sparingly. A single depressed ring on an otherwise promising figure may be eliminated by cutting out two or three facets along the path of the ring, thus reducing the abrasion of that particular zone. A raised ring is more difficult to deal with. If not far from the circumference it may be removed by the "overhang" method, working so that the edge of the tool just traverses along the raised zone. It may also be dealt with by very cautious use of a polisher all cut away except a ring of the same size. A very few strokes at a time should be attempted on this, or we may get a depressed ring instead.

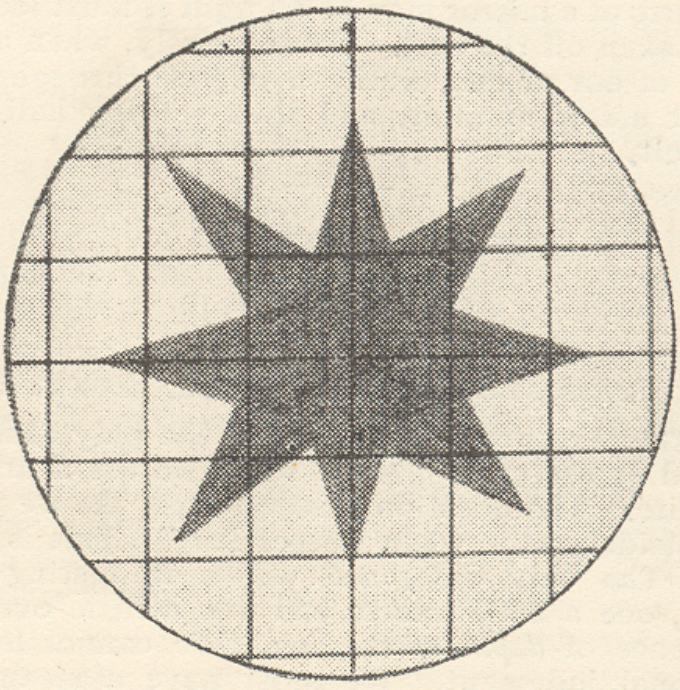


FIG. 16.—Another way. This is more suitable for small sizes, and for object-glasses.

Having overcome these difficulties we will suppose we are now approaching the desired paraboloid. There are several difficulties of another kind to be met before we "get there."

If the worker be at all observant he will have noticed before this that the figure seen on testing immediately after removing the mirror from the tool is quite different from what appears some time later, when the mirror is allowed to rest awhile. The cause of this is, briefly, temperature. The friction of mirror on tool produces quite a considerable amount of heat, and we shall find that there is a very definite law connecting the figure of a mirror with its condition of temperature relative to the surrounding atmosphere. Briefly stated, the law is as follows :—

When a mirror is cooling its figure is temporarily pulled "down-hill," or in the direction of the hyperbola. When a mirror is warming its figure is temporarily pulled "up-hill," or towards the sphere. (This, by the way, is the real reason why a slight under-correction is always given to specula by the best makers. A mirror, when in use on the heavens, is nearly always cooling slowly, with the atmosphere of a clear night. Consequently if its figure were a full paraboloid it would always, under working conditions, be a little over-corrected. To avoid this it is left a little under-corrected in the workshop.)* The result of this law is that we can never see the real figure of a mirror immediately after taking it off the tool. In fact, if we see a parabolic figure then, and leave it a while to cool, we shall find that it has changed to a sphere, or even an oblate spheroid. To obtain a paraboloid when cool we must have a very pronounced hyperboloid on taking off the tool. At least half-an-hour must elapse before the true figure can be seen. Ignorance of this has caused endless trouble to beginners; for in order that the figure of a mirror may be all right it must look all wrong when just taken off the tool. Consequently, when approaching completion of our mirror, we have to pass through a period of working for a few minutes, and then waiting half-an-hour to see the result.

CHAPTER VI.

How to Recognise the Paraboloid. Zonal Testing.

The "Temperature Effect" is not the only difficulty to be encountered at the critical stage when we are nearly "there," but not quite. The question arises, "How are we to recognise the paraboloidal curve when we get it?" This is a very real difficulty. The only difference visible in testing between a true curve, one a little under, and one a little over-corrected, is a difference of *depth of shading*. We cannot leave this to mere personal judgment. We must have a means of distinguishing accurately. And this is the more necessary as the depth of shade in the parabola *varies enormously with the ratio*

* This has been disputed, but is fully confirmed by Prof. G.W. Ritchey: the worlds greatest authority on the reflector. See p. 45. and Appendix II.

of focal length to aperture. The same shadows which would indicate a beautiful parabola in a mirror whose ratio was *f.* 8 (as the photographers conveniently call it) (*i.e.*, whose focal length was eight times its aperture) would mean a deep hyperbola in a mirror of *f.* 9. And when we get much beyond *f.* 10 or *f.* 11 we can *see no parabolic shadows at all.* If shadows can be seen in such a mirror it is hyperbolic. In other words, the difference between a sphere and a paraboloid in such a mirror is too small to be seen. It can, however, be measured. We have already learned that when testing a spherical mirror, with the knife-edge just cutting the converging beam exactly at the centre of curvature, the mirror is seen to darken evenly all over. In other words, the difference of radius of curve for centre and all zones distant from the centre is zero. In the paraboloid and hyperboloid the radius of curvature increases outwards from the centre. In the oblate spheroid it diminishes outwards. Therefore, if we place over the mirror a stop which covers all its surface except a small area about the centre, and adjust the knife-edge till this area darkens evenly, and then substitute for the first stop another which covers all except a strip of margin, if the mirror be a paraboloid we shall have to move the knife-edge a little way *further from* the mirror to get his marginal strip to darken evenly ; and if it be a hyperboloid, a little further still. And if we know *how much* the knife-edge must be moved back for a paraboloid we shall have an accurate means of recognising the desired curve when we see it. Now, the mathematicians have given us this information, and it is enshrined in the simple and easily remembered formula $\frac{r^2}{R}$ where r is the radius of the mirror, or of any zone thereof, which we desire to test, and R is its radius of curvature. For example, if we are testing a $6\frac{1}{4}$ in. mirror of 4 ft. focus (*i.e.*, 8 ft., or 96 in. radius), $\frac{r^2}{R} = \frac{3^2}{96} = \frac{9}{96} = 0.093$ in. Therefore, if we find that, after adjusting the knife-edge to the radius of the centre we have to move it back .093 in. (nearly 1-10 in.) to get the marginal zone to darken evenly, the mirror is a paraboloid, always provided that the mirror, tested without a stop, shows a *regular* curve, *i.e.*, is free from rings, hills, hollows, or turned edge. Some workers prefer to test a whole series of zones, and tables are given of the values of $\frac{r^2}{R}$ for all diameters of zone and all focal lengths. It is, however, very trying to the eyes to test a long series of zones, and it is not necessary. For the open shadow test tells very clearly and unmistakably if the *general curve is regular.* And then it is only necessary to test the difference between the centre and marginal zone, for if this is right and the curve is regular all the other zones *must* be right.

Now we can understand the object of the metal straight-edge attached to the stand of the knife-edge (see Fig. 9). We pin a white card to the top of the testing table with a couple of drawing-pins, stand the knife-edge on it, and when we get it

adjusted for the centre of the mirror, hold it firmly down, and draw a sharp-pointed pencil along the straight-edge. Now we adjust for the marginal zone, and repeat the process, taking care to keep the block in which the knife-edge stands parallel to the edges of the card. Now we have a pair of parallel lines on the card, and the distance between them will be $\frac{r^2}{R}$ if *our mirror is parabolic*. Many and elaborate are the arrangements devised by Wassell and others for making this simple measurement. Micrometer-screw movements in two directions, springs to take up slack, scales, and microscopes to read them. The writer has tried them all, and ended by "chucking" them in favour of the simple method above described. The straight-edge, pencil, parallel lines on the card, and a pocket-lens and scale of 50ths of an inch, to measure the distance apart of the lines, are sufficient. The simpler a method is the better, provided it gives the desired result. And in all this little book the object before the writer has been to reduce everything to the maximum of simplicity consistent with efficiency. The stops above referred to may conveniently be made of pasteboard. For each size of mirror two circular pieces may be cut, the exact size of the mirror. One has a circular hole cut in the centre, a little larger than the minor axis of the flat which is to be used with the mirror, *e.g.*, for a $6\frac{1}{4}$ in. mirror a hole $1\frac{1}{2}$ in. diameter will be suitable. From opposite sides of the margin two pieces are also cut, as shown in the figure. Fig. 17. The shaded portions are those cut out. The width of the marginal zone may be $\frac{1}{2}$ in. for mirrors of 4 to 5 ft. focus, but must be wider for ones of longer focus, owing to the greater distance from which

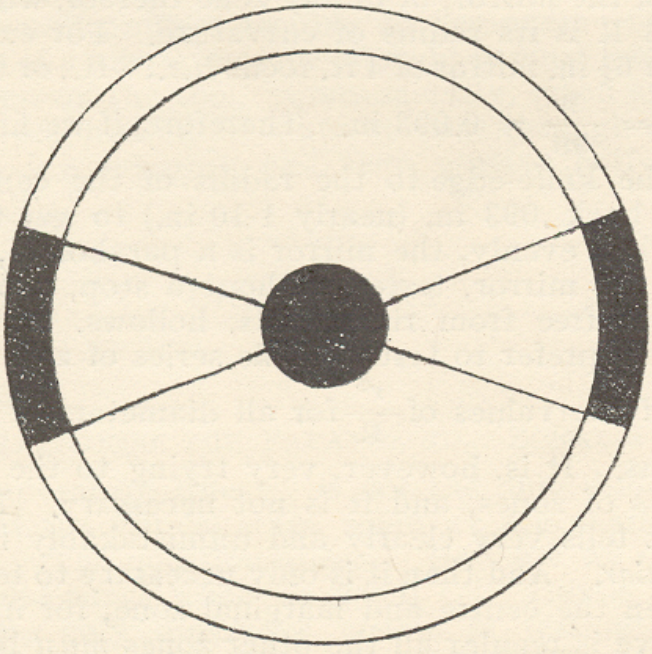


FIG. 17.

it must be read. The other disc may be cut thus (Fig. 18). The cross-lines and the inner circle are only for guidance in cutting. The stops having been prepared, the mirror is placed

on the easel, a card is pinned to the top of the testing table, and the knife-edge put in position and adjusted to the proper position for shadow testing. Care should be taken to place the straight-edge parallel to the sides of the card, and the sides of the latter parallel to those of the table. The stop is now placed on the mirror. (The writer prefers stop I., but II. is the form most frequently used). Let us suppose we are using No. II. What shall we see? Let us consider first zones A and B. As the knife-edge is advanced across the beam of light, one of three things will happen. Either zone A darkens while B remains bright, or *vice versa*, or they both darken equally. The observer must practise his judgment in deciding which of the two is the darker, as in reading a Bunsen's shadow photometer. If both are equally dark, the knife-edge is *at the focus of this zone*, and the pencil may be used to mark the position of the straight-edge. Now *before moving the knife-edge*, observe the appearance of the zones C and D. If the mirror is parabolic or hyperbolic, the knife-edge when at the focus (centre of

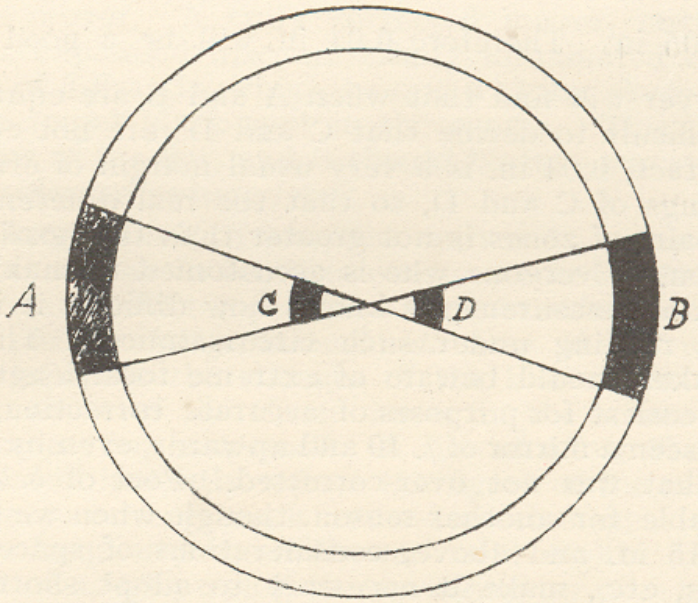


FIG. 18.

curvature) of the zone A B will be *outside* the focus of zone C D, because in these curves the centre has the shortest radius. Therefore, when A and B are *equally dark*, C will be *darker than D*. The knife-edge must therefore be moved *towards the mirror* a little to make C and D become equally dark. When they are judged equal, the pencil is used again. If the distance between the pencil lines is equal to $\frac{r^2}{R}$ the mirror is exactly corrected. In practice it is always advisable, for the reason already stated, to leave the correction a little less than $\frac{r^2}{R}$ Thus in a mirror where $\frac{r^2}{R}$ = 0.10 in. 0.08 in. would be a good correction. Even

0.06 in. might pass as sufficiently corrected. In any case a number of readings should be taken, and the mean of them all adopted as the true reading.

The chief difficulty the tester will meet with is the difficulty of deciding the exact point where C and D are equally dark. It is far easier to decide between A and B, owing to the more obtuse angle subtended by these at the centre of curvature. Therefore, it is well to take a number of readings of C and D, sometimes taking the knife-edge well inside their focus and working outwards, and at other times well outside and working inwards. It is for this reason also that we recommend the stop of the form No. I., as it is somewhat easier to decide when the shadow in the central hole *travels neither way*, but comes on equally all over the hole, than to decide between the relative shades of the two slots C and D. If these slots are too narrow, the eye is very apt to be misled.

In the case of a long focus mirror, decision is naturally very difficult. Take, *e.g.*, a 6 in. of 6 ft. focus. In this case $\frac{r^2}{R} = \frac{7.29}{144} = 0.05$ in. Therefore 0.04 in. will be a good correction. The observer will find that when A and B are equally dark it will be difficult to decide that C and D are not equally dark also. In fact, 0.04 in. is a very usual margin of error between two readings of C and D, so that the real difference between the two pairs of zones is not greater than the possible error of observation. Everyone who is accustomed to making delicate instrumental measurements knows how difficult it is to obtain a reliable reading under such circumstances. Therefore the mirror-maker should beware of extreme focal lengths; *f.* 8 to *f.* 9 is the easiest for purposes of accurate correction. We have never yet seen a mirror of *f.* 10 and upwards, even by well-known makers, that was not over-corrected. Foci of *below f.* 8 are objectionable for another reason, though when we get to apertures of 15 in. and above, considerations of space, weight of mountings, etc., make it necessary to adopt short foci. The trouble with these is that the wide-angle cone of rays upsets most eye-pieces, unless they are specially calculated for the purpose. Ordinary negative eyepieces give quite an unpleasant amount of false colour on mirrors of *f.* 7 and *f.* 6, and really spoil the perfect achromatism of the reflector. Achromatic eye-pieces should be used with all mirrors of focus below *f.* 8 if the finest definition is to be obtained.

In conclusion of this part of the subject, let us again repeat the warning given before with respect to temperature. It is absolutely necessary, the *sine qua non* of success, that testing shall be carried out in a place in which equilibrium of temperature can be maintained. The best of all places is a cellar completely underground, and free from draughts. If this is not available, the next best place is a basement room, partly underground. And if it must be above ground, it should be done in a substantial stone building, with as little window space as possible. It is *quite impossible* to get true readings in a living

room, or any place artificially heated. It is equally impossible in a lightly-built workshop of timber or galvanised iron. In fact, such a building is hopeless for the mirror-maker's work, except for the roughest parts of it. Polishing, not to mention figuring or testing, is impossible in a place where the temperature may vary 20° or 30°, according as the day is sunny or cloudy. Testing *in the open air* is equally impossible. And this last is tantamount to saying that *testing on a star* is useless, for a star-test is necessarily in the open air. It sounds no doubt plausible to say that as a telescope is made for observing stars, its performance on a star must be the best criterion of its quality. But it is to be noted that this plea is used by those with the most limited experience of up-to-date methods of testing. And when we find that a star-test is capable of pronouncing *one and the same mirror on the same night by turns under-corrected, truly corrected, and over-corrected,* we see how little reliance is to be placed thereon. The writer has often had this experience when using various mirrors in the open air. It is easy enough to see, by the out-of-focus images of a star, what is the state of correction of the mirror. A truly corrected mirror, out of focus, will give an expanded disc, uniformly illuminated except for faint traces of diffraction rings, having a clean, sharply defined edge, and a round black spot in the centre. This black spot is the shadow of the flat, and it should be *the same size at equal distances inside and outside focus.*

If it is larger *inside* focus, the mirror is under-corrected. If it is larger *outside* focus, it is over-corrected. And many a time on a night when temperature was variable the writer has watched a mirror *change through all these phases* within not very many minutes, the changes of the black spot answering faithfully to those of the thermometer in the screen close by. And the changes are *not small.* A rise of 4° or 5° in the air temperature will instantly reduce the figure of the mirror from a true curve to a very much under-corrected one. And such changes are frequent, especially on mild nights in autumn. The passage of a light cloud, the springing up of a breeze, the formation of a fog, will raise air temperature suddenly by several degrees. And the mirror instantly responds by lowering its correction. And in the opposite event, of temperature falling sharply, the mirror goes the opposite way, the correction being raised. But this is less serious, because, as already pointed out, most mirrors are slightly under-corrected. The change, of course, is temporary, and is only due to the fact that, a mirror being a thick and massive piece of glass, and glass having a high heat capacity, its warming and cooling cannot keep pace with that of the air, but *lags behind it.* In point of fact, makers of specula, without knowing it, have been in the habit of *correcting them for a falling temperature.* If it were desired to use a speculum for daylight work, *e.g.*, for solar observation, it would be advisable to considerably over-correct, or in other words, to correct for a rising temperature. And in making a mirror for use in a climate such as that of Mexico, where temperature drops very rapidly after sunset, a figure in the neighbourhood

of a sphere might perform better than a paraboloid. A striking illustration of this propensity of mirrors may here be mentioned. A 9-in. mirror made by Mr. Maurice A. Ainslie, a well-known and expert amateur speculum maker, was sent to the present writer for examination, and was found to be a little over-corrected. At the owner's request it was re-touched, and the correction lowered. Some time afterwards the author was introduced to Mr. Ainslie at a meeting of the British Astronomical Association, and mentioned this mirror and its defective correction. It proved to be one which Mr. Ainslie had specially made for observing planets *in the morning twilight*, when temperature would be beginning to rise after the night, and was over-corrected because it was found to perform best in this condition.

It sometimes happens that a mirror is made of inferior glass or glass of unusual quality, and such mirrors will often have a whole set of peculiarities of their own. A thin mirror will sometimes perform quite well with one particular diameter vertical, but in all other positions give double images or reveal other signs of flexure. And twice within the writer's experience a mirror was submitted to him which *would not keep a figure*. A 9-in. mirror was on one occasion refigured *three times*, and on each occasion after a week or two was found very much under-corrected. At last the plan was adopted of strongly *over-correcting* it, and then the figure after a time came back to a paraboloid, *and stayed there*. Much trouble will be saved by adopting a good quality of glass. Only the best plate glass should be used, and if assurance must be made doubly sure we can purchase a cast disc of Chance's hard white crown, which is purposely made for mirror work and guaranteed well annealed. The price, though about double that of a plate disc, is still moderate, and the disc may be thinner than the dimensions we have laid down for plate discs, and still be safe from flexure. Such a disc may be trusted not to play tricks.

In concluding this part of the subject, let me give one caution to the beginner: *Do not be too ambitious*. A 6-in. mirror is quite large enough for a first essay. If not a success, as is more than probable, the loss is only a few shillings, and some time and labour. The difficulty of working a mirror increases by leaps and bounds with its aperture. 6-in. to 8-in. soon become fairly easy with some experience. But 12-in. is a tough proposition even for a skilled hand.

CHAPTER VII.

SILVERING.

The mirror completed, it now only remains to provide its surface with its reflecting film of silver. The necessity for this film, together with its fragility and liability to tarnish, is to many the chief drawback to the reflector. The process of silvering is not, however, difficult, and anyone who adopts the plan now to be given, together with the protective pad, later to

be described, need have no trouble either in producing or preserving a reflecting surface. The process which follows is the writer's modification of that of Brashear. It is perfectly safe and quite simple and easy.

(A) Chemicals required :—

1. *Nitrate of silver* ($AgNO_3$) may be had sufficiently pure at any chemist's shop.

2. *Caustic potash* (KOH) or *caustic soda* (NaOH).

Either of these may be used indifferently, but they must be *pure*. Potash was always used before the war, but the stoppage of supplies obliged telescopists to cast about for a substitute, when soda was found to answer quite as well. As it is *always* cheaper than potash, it is likely to remain in favour. No alteration is necessary in either quantities or procedure. ~~John J. Griffin & Sons~~, Kingsway, W.C., will supply it of satisfactory quality. Even when chemically pure, its price is quite moderate.

Messrs Griffin & Tatlow

3. *Liquid ammonia*, .880. To be used in a 10 per cent. solution. Obtain ~~from Jonathan Fallowfield, 146 Charing Cross Road, E.C.~~, a "Haddon and Grundy's 10 per cent. ammonia bulb."✕ This is a small glass bulb which will *just* float in ammonia of the strength specified. Keep it in the bottle of solution and adjust before using by adding a few drops of ammonia or water till the bulb just hangs suspended, neither rising to the surface nor descending to the bottom. This exact standardising of the ammonia removes 90 per cent. of the difficulties of silvering successfully.

4. *Nitric acid.* Strong, and as nearly pure as can be obtained. A few ounces will last a long time.

5. *Cane sugar.* The best crystallised white coffee sugar is to be preferred. Next best is sugar candy. In default of either, loaf sugar, but this is not recommended.

6. *Tartaric acid.*

7. *Alcohol.* "Industrial spirit," or methylated spirit *not containing naphtha* is excellent. If not obtainable, the much dearer "rectified" spirit, or absolute alcohol must be used.

8. *Pure cotton wool.* Buy it from a *chemist*, not from a draper.

(B) Stock solutions :—

The following must be made carefully and kept in such quantities as the work to be done requires.

1. Silver nitrate, 1 oz. ; distilled water, 16 fl. oz. Keep in stoppered bottle in the dark or in a bottle of *yellow* glass.

2. Caustic potash (or soda), 1 oz. ; distilled water, 16 fl. oz. Keep in corked bottle, *not* stoppered.

3. Reducing solution.—Sugar (as above), 5 oz. ; tartaric acid, ½ oz. ; distilled water, 5 fl. oz.

Put the water in a large glass measure. (You should have two large—10 oz. or 20 oz.—and two small ones—1 oz. or 2 oz.). Add the sugar and tartaric acid and note the level of the water. Now place the contents of the measure in a new and clean

✕ These were formerly obtainable from J. Fallowfield 146. Charing Cross Rd E. C. They went out of manufacture during the war. They can now be had of the Author! at the Observatory. Armagh.

enamelled saucepan, which must be kept strictly for this purpose alone. Boil it over a gas-ring, oil stove, or Bunsen burner till all the sugar is dissolved, and about five minutes longer. Let cool.

When cold, pour back into the measure and add distilled water to make up to the bulk noted before boiling. The water may be poured, a little at a time, into the saucepan and rinsed into the measure. In this way no sugar is lost.

Now add 5 ozs. of alcohol and stir well with a glass rod. A clear, viscid solution of a golden yellow colour results. Place in a stoppered bottle and keep a week before using.

N.B.—The solid oz. in the above quantities is the apothecaries' oz. of 480 grains Troy, containing 8 drachms, and equals 31.152 grammes.

To Prepare the Mirror for Silvering.

Careful dispositions must be made beforehand (1) to *support the mirror* safely face down in the silvering vessel; (2) to *ascertain the exact quantity* of solution required; and (3) to have the optical surface *chemically clean.*

(1) The best kind of dish is a circular one of glass, flat-bottomed, 2 to 3 in. deep and large enough to hold the mirror, with a little room to spare. What are known as "crystallising dishes" can be had from all medical stores, and for mirrors up to 8½ in. diameter nothing better can be desired. They are made up to 9 in. diameter, and Messrs. A. Gallenkamp & Co,. 21 Sun Street, Finsbury, E.C., will supply them if not obtainable elsewhere. For larger sizes *tin-plate milk pans*, which can be had of all sizes up to 24 in. at hardware shops, will answer well if coated inside with paraffin wax or beeswax well melted on. Enamelled iron is inferior, as the solutions attack the surface. An ordinary soup-plate will do for a small mirror.

The dish is placed in position on the table or shelf, where it will stand when holding the solution, and a few blocks of wood handy beside it.

Now to secure the mirror to a safe support. Get a piece of nicely-planed wood 1 in. x 2 in. and several inches longer than the diameter of the dish. To the middle of it screw a disc of wood about 3 in. diameter and ½ in. to 1 in. thick. The disc is to be cemented with pitch to the back of the mirror. Warm the latter over the oil stove, smear on a little turps, lay it face down on a clean, folded towel, and pour a little melted pitch on the middle of the back, and press wooden disc firmly on at once. Enough pitch should be used to exude all round disc, and take care to have the pitch melted ready to pour directly the mirror is warm. Here, as always when the mirror is to be warmed, it should be done over the gas-ring or oil-stove turned *very low*—almost out. Great care should be taken not to overheat, nor to forget the mirror on the stove. Plate-glass will stand a lot of rough usage in the way of heating and cooling, but if heated very hot it may possibly crack. The moisture which deposits on the cold glass when placed over the lamp is a good guide. When it is *just disappearing* the mirror is hot enough.

(2) When pitch is set and mirror cool, support it face down in the silvering dish, placing blocks, if necessary, under the ends of the wooden bar till the face of the mirror is about ½ in. clear of the bottom of the dish, and quite level. Pour in water till the face is immersed, seeing that no bubbles remain under it. Measure this water carefully, for this will be the *bulk of the final solution* when mixed. Write quantity down on a slip of paper.

Leave blocks and dish in position, so that mirror can be instantly replaced without hesitation or fumbling, as no time must be lost in getting it into the solution once the latter is mixed with the reducing agent.

(3) Now comes the all-important *cleaning*. On its thoroughness depends the success of the operation—a fine even film or a thin and patchy one. Lay the mirror, face up, supported by its wooden bar, across a large basin of glass, earthenware, or enamelled iron. It is in order that this may be possible and safe that the bar is made wide and flat. Pour on the face of the glass a few drops of nitric acid. Make a mop of cotton wool, also moistened with nitric acid. This may be done by pushing a bunch of cotton wool into the mouth of a test tube or tying it round a stick. A glass rod is objectionable, as it may protrude through the cotton and scratch the mirror. An aluminium rod is not bad, and the acid has ~~no~~ action on it. A rod *cast in lead* would also answer. With the mop rub the acid all over the face of the mirror, especially along the edge. Do this very thoroughly, and do not be sparing of time over it. Rinse well with water, and note whether the water clings all over the glass in an even film. If it does so, and shows prismatic colours when it begins to dry along the edge, the mirror is clean. If, however, dry patches appear suddenly here and there, these spots are still greasy. A very dirty mirror may with advantage be well lathered with common soap, such as Sunlight or Hudson's Dry, and the lather rinsed off under the tap before applying the acid.

When clean, place mirror face down in a dish of distilled water till required. A few drops of ammonia in this water will be useful to get rid of any traces remaining of the nitric acid. A mirror which has an old film on it is easy to clean. Merely dissolving off the film in nitric acid and rinsing well with water is usually sufficient.

To Prepare the Bath.

Perhaps the best way to make the procedure clear is to describe an actual operation. The mirror, a new 6¼ in., has been cleaned, and is waiting face-down in a glass dish of distilled water, supported safely clear of contact with the bottom by its wooden bar, which rests upon the sides of the vessel. The silvering vessel is another circular glass dish, flat-bottomed, and with vertical rim. It is 7¼ in. diameter and 2 in. deep. It rests on a level wooden shelf, and a pair of wooden blocks, of the correct thickness to support the mirror, with face ½ in. clear of the bottom, stand one on each side. A previous trial with water has indicated that 15 fl. oz. will immerse it properly.

Now the bath must contain 4 *grains* of silver nitrate, *per fl. oz.* of liquid, to give a satisfactory film.

On a slip of paper have been written, after the trial immersion, the words, " Fifteen oz. bath = 60 grains $AgNO_3$."

The stock solution contains 30 grains per fl. oz. We therefore require 2 oz. of it to make up the silver portion of the bath. Write on the slip :—

" Two ounces $AgNO_3$."

" Two ounces KOH."

And as the bath requires 1 drachm of reducing solution per 20 grains of silver salt, we add,

" Three dr. red. sol."

The paper slip with these particulars written down is a useful safeguard against mistakes or forgetfulness.

We now pour out into a measure 2 *oz. of the stock solution of silver.* To this we add from our bottle of 10 per cent. ammonia (standardised by means of the Haddon and Grundy bulb), $3\frac{1}{2}$ *drachms for each fl. oz. of silver*, or 7 dr. in all. This, if measured carefully, gives just the right amount to form " ammonia silver-nitrate," and the solution, after stirring, should remain *slightly cloudy.* If it does not, add a drop or two of silver nitrate, and stir till the cloudiness persists.

You now have a solution of " ammonia-silver-nitrate." (N.B.—Never keep a solution of this substance, nor allow it to dry up, as a dangerous explosive is liable to be formed in it.) Now take, as noted on your slip of paper, 2 oz. *of caustic potash* (or soda) solution, and to it add 2 *drachms* of 10 per cent. ammonia, *for each fl. oz.*, or 4 drachms ($\frac{1}{2}$ oz.) altogether, and stir.

Mix the two solutions thus prepared together, and stir well. If the solution *remains clear* on mixing, add a drop of silver nitrate, and stir, and go on adding till the clear solution becomes, and remains, *turbid, or slightly muddy.* Possibly, this turbidity may appear at once when the solutions are mixed, in which case no further preparation is needed. If it is too muddy no harm is done, but it *must not be clear.*

Now note how much solution you have, and remember the quantity noted on the paper as the total bulk of the bath, viz., 15 oz. We will have between 5 oz. and 6 oz. in the quantity already mixed, so we require 9 oz. or 10 oz. more. Make it 6 oz. even, by adding a little distilled water, and empty it into the silvering dish. Now we proceed to make up the *reducing solution*, the bulk of which must be 9 oz., to make the final quantity correct. Looking at the paper slip we see " Three dr. red, sol." So we measure out this quantity. (We may take a little more, as the reaction is not an exact molecular one, and a little more of the sugar solution will only hurry up the depositing of the film.) Add enough distilled water to make 9 oz., and stir very well.

Now pour this into the silvering dish, where the silver solution already is, and rock the dish a little. The liquid at once begins to darken, and in a few seconds is quite black.

Take the mirror up at once and lower it into the solution obliquely, one edge first, to avoid catching a bubble under it. See that it sits level, and now write on your paper slip a note of the *time* of immersion. Leave it alone till finished.

The value of the Haddon and Grundy bulb is that it saves time and uncertainty at the two points where ammonia is added to the solution. If care is taken with the measurements, and especially if the dilute ammonia is measured in an accurate measuring glass, the requisite slightly cloudy solution will be obtained at once. But even if not, a drop or two extra of silver nitrate will cause the cloudiness to appear. These two additions of ammonia are the *danger points* of the process, for an overdose of ammonia is fatal. The cloudiness indicates that the *silver is slightly in excess*, which is the proper condition for a successful reaction.

If the Haddon and Grundy Bulb is not to be had it will be necessary to add ammonia very carefully, especially the second time, after mixing the silver solution with the potash. At the *first ammoniation* we are adding ammonia to a clear solution, and must go on adding till the brownish cloud at first produced by it, *nearly, but not quite*, disappears. At the *second ammoniation*, if the ammonia has not been previously mixed with the potash as above described, we get, when the potash is added to the silver solution, a thick black or dark brown precipitate; a nasty-looking mess, which must be cleared by adding ammonia till the black precipitate *nearly* disappears. But the trouble is that we *never know the right moment* to stop, for a quantity of black flakes will persist in remaining; and if we dose the solution with ammonia to get rid of these, we shall find we have added a huge excess, and may ruin the whole process. This *want of definiteness* in the disappearing point of the potash precipitate is the greatest difficulty in silvering. All this trouble is saved by mixing the ammonia with the potash *before* adding the latter to the silver, and all we require to know is the exact strength of the ammonia in order to know how much to use. We get *no black mess*, the solution remaining clear, or nearly so, and we get a very definite indication (one drop of extra silver nitrate often changing the clear solution to cloudiness) instead of a very uncertain and misleading one. This exact information the little bulb gives us. Without it, it is hardly safe to put the *ammonia into the potash*; but we must mix the potash with the silver, and then go through the troublesome and uncertain job of clearing away the black mess little by little with ammonia.

Having placed the mirror in the bath of solution, we now want to know *how long to leave it there*. This is not easy to decide. The rate of deposit is very variable and depends on several factors. Temperature, the quantity of reducing solution used, the quality of the potash, the accuracy of the ammoniation, all have a say in it. The result is, that it often varies most capriciously. I have often found it change from two hours to twenty minutes, or vice versa, on using for the first time a fresh sample of chemical.

It is a good plan to keep a few glass slips handy, carefully cleaned, and to insert the end of one of these into the bath for about ten minutes. If there is no film on it when taken out the deposit is complete. Lift the mirror out and sluice it well with water. Look through it at a light or at the window. It ought to be very nearly or quite opaque. If, as sometimes happens, the film, for some reason, is thin, do not let it dry, but put it at once back into the dish of water in which it was placed while making up the solutions. Rinse out the silvering dish (no need to remove the film of silver—only the spent solution and mud), and make up a fresh lot of solution, half or quarter strength, according to the state of the film, and immerse again. There is no harm even in lifting the mirror out for inspection, and replacing it in the solution if it does not appear to be ready. I am aware that this is clean contrary to the lore of the old masters; but, as I have, like Father William, "done it again and again," and found no harm result, I believe I am safe in recommending it. And this is not the only "precept of the elders" which I have had occasion to reject. During a lengthened course of experimenting I have frequently disobeyed solemn precepts of Draper, Francis, Wassell, and others just to see what would happen. Very often nothing happened. Nothing very terrible ever happened. And a good may quite new improvements resulted. The mixture of wax with pitch for polishing, for example, is a heresy excommunicated by all the former elect; but that does not prevent it working beautifully. But a truce to digressions. *Revenons a nos moutons.*

What we may call the "instalment plan" in silvering gives very fine films and requires a minimum of interference with them. It will be found that if the mirror is removed from the bath *before* the silver is quite completely deposited the film will be very brilliant and require next to no polishing, but it may be thin. If it is left in after deposit is complete a whitish film forms on it, and this is more difficult to polish off the longer the immersion continues, though a mirror may be left in all night without any irreparable harm being done.

But in any case polishing is always objectionable, and the less of it required the better; therefore if one does not mind being a bit extravagant in chemicals one can proceed as follows: Make a solution half or two-thirds strength, and give the mirror a *short* immersion—*i.e.*, remove it when you judge that deposit is not quite complete. Put it aside in the dish of water, and make up another bath, and repeat the immersion, removing the mirror, as before, when not quite complete. Do it a third time if necessary. This gives a very brilliant film of any required density and no pinholes or air-bubbles.

When finished and thoroughly well sluiced with clean water (tap-water this time, not distilled) set the mirror on its edge in a dry, airy place, resting on a pad of blotting-paper, and on no account touch the film with anything till it is quite dry.

To Polish the Film.

As has been already said, if we have hit off the right moment

to remove the mirror from the silvering bath, very little polishing will be required. This is a great advantage, as there is always more or less risk of injuring the fragile skin of silver in polishing it. Make two pads of fine, soft chamois or washleather, stuffed tightly with cotton-wool. Keep them in a clean jar or tin covered to exclude dust. One is to be used plain, the other covered with the very finest possible rouge. A regular speculum-maker has no difficulty in obtaining the right stuff. With constant rubbing down on the tool a certain amount of rouge becomes so fine that it takes several days to settle out of suspension in water. When this is observed to be the case some of the red-stained water may be poured off into a glass dish and set aside in a warm, dry place, covered with a plate of glass. When observed to be settled clear, the water is poured off and some more of the same stuff added, and let settle in its turn. When enough sediment is seen to have collected let it remain till dry, always, of course, covered. The polishing pad is dipped in this, and takes a charge which will last almost *ad infinitum* without needing renewal.

If this method is not available we must put some dry rouge into a jar, fill up with water, and stir well. After settling, take on the finger-tip some of the red scum and froth which floats and smear it on a clean piece of glass. Dry carefully, and rub the polishing pad on it.

First rub the film carefully all over with the plain pad in small circular strokes. Then follow with the rouge-pad. Very little of the latter will be needed if the mirror was not over-immersed. If it was, there will be a whitish film on it which will require a good deal of polishing to get rid of it. But even many hours' over-immersion will do no harm beyond a little extra trouble in polishing.

Once polished, leave the film quite alone. *Never attempt to get rid of tarnish by re-polishing.* You will lose far more light by *thinning* the film than you will gain by polishing it. Even when appearing very badly tarnished a silvered mirror retains nearly all its original light-grasp. Silvered glass, even at its best, never *looks* as bright as speculum metal. But appearances are deceptive. Silvered glass *looks dull* and *is* bright ; speculum metal *looks bright* and *is* dull. When equally well polished, a silver film reflects *about double* the light of a speculum metal surface the same size. Even when very badly tarnished, the silver film is still vastly superior to the metal at its best. This is a fact not always realised even by professional astronomers.

A Few Hints.

Distilled Water.—It may not be easy to procure this in, quantities sufficient for operating on a mirror of any size, but, unless one resides in a large town or near a manufacturing district, *clean rain-water* will answer all purposes if certain precautions are observed in collecting it. In the country rain-water off any clean roof will do. A glass roof is best ; next best is a galvanised iron roof, and next a slated one without chimneys and free from moss and lichen. The best time to

collect is on a very wet day after it has been raining for several hours. Do not dip the supply from a barrel or tank, but let it run from the eave-gutter direct into a clean vessel. Store a few gallons in clean corked bottles, replenishing the supply as occasion serves. Quart whisky bottles answer well, as a trace of alcohol does no harm. If you are near the sea collect water only when the wind is *off the land*. Traces of chlorides are the most injurious impurities likely to be present, and they are sure to be there "when the wind bloweth in from the sea." Test a sample with a drop of silver nitrate. If no cloudiness forms in it the water is all right.

Care of Film.

Next in importance to success in producing a film is success in keeping it. Two or three years are generally considered to be a good life for a film. But this can be very greatly extended, at least in the country, by suitable precautions in protecting the silvered surface. Its two enemies are *sulphur* and *moisture*. The first is only troublesome in a town atmosphere. A close-fitting cover, always on when the telescope is not in use, is the best remedy.

Moisture (the dewing of the mirror) cannot always be prevented unless the telescope is housed in a covered observatory. In the open air a rise in temperature of a few degrees, such as often happens on a fine night in autumn, will almost certainly dew the mirror. The only thing which can then be done is to close up the telescope and retire, especially as the rise of temperature will also upset the correction of the mirror for a time and play havoc with definition. But, short of a sudden rise of temperature, a mirror at the bottom of its tube, especially a wooden tube, is almost beyond the reach of dew. The flat *always* dews first.

The close-fitting cover, which every mirror should have, ought to be provided with an absorbent pad inside to take up moisture. I find the following plan so effective that I believe a film thus protected will last almost *ad infinitum*, certainly for very many years. Cut from stout pasteboard a circle large enough to fit loosely inside the mirror cell. Cut also similar circles from white blotting-paper and clean white cotton-wool. Make a sandwich of them, cardboard one side, blotting-paper the other, and cotton-wool between, and stitch them together. Attach a loop of string to the pasteboard side. Before putting the cover on the mirror lay this pad on the face of mirror, blotting-paper next the surface of the glass, and put cover on over-all. The string is for lifting off. If this pad be now and then well toasted before the fire or exposed to hot sunshine for an hour or two it will be dry enough to absorb all moisture within the cover and permit none to remain on the mirror. If the mirror ever gets dewed when open, the pad placed on it for a few minutes will cause the dew to vanish completely. A similar pad is not without its uses inside the cover of an object-glass.

Protected in this way, I have had films in use for years, and just as bright as the day they were deposited.

Residues.—In a workshop where much silvering is done it is worth while to preserve these. The mud left in the dish after silvering is *pure metallic silver* in a finely-divided condition. There is also a film on the bottom and sides of the vessel. Pour off as much of the liquid as possible without disturbing the sediment, fill up with water, and add a few drops of nitric acid. After standing for a few hours stir well, when the film will strip off in flakes, and the mud will collect in pellets, and the whole can be easily washed down into a large glass jar. Add a little solution of common salt to the contents of the jar to make sure that the silver is all precipitated. When enough has accumulated a wholesale chemist, such as the before-mentioned ~~John J. Griffin & Sons~~ Griffin Tatlow, will purchase the contents of the jar for cash or give its equivalent in silver nitrate. In this way I have received as much as ¼-lb. of this valuable salt in exchange for quite a small jar of workshop residues. One saves at least three-fourths of nitrate used.

N.B. Though quite safe with the above process, it is dangerous to do the if Brashear reducing solution is used

CHAPTER VIII.

The Achromatic Object Glass.

Notwithstanding all the merits of the reflector, its power, its magnificent capacities for definition, its colourless images, its simplicity and consequent ease of manufacture, and cheapness, there will always be a large public to whom the word "telescope" means a refractor. And the refractor is certainly the most "fool-proof" form of the instrument. It has no silvered surfaces to deteriorate, and its adjustments, once made, are permanent, barring accidents or gross carelessness. But whereas there is an extensive literature in existence, however difficult to get at, for the aid of the amateur workman who desires to make a reflector for his own use, few indeed have ever regarded the achromatic lens as a practical proposition for the home worker. It is generally regarded as within the capacity of the professional optician only, and the high price of the necessary discs of optical glass is prohibitive to the would-be experimenter unless he is content with small apertures. In addition to this barrier to the amateur of limited pocket, the expression "calculating curves" has been a bogey which has frightened away many a recruit. It seems to imply a vista of abstruse mathematical formulæ for which only the brain of the college don is adequate. But, as a matter of cold fact, the calculation of curves to correct *chromatic* aberration for a given focal length involves nothing more abstruse than the modicum of algebra required to solve a simple equation, and sufficient arithmetic to cope with addition, subtraction, multiplication, and division of decimal fractions. The correction of *spherical* aberration does indeed involve complicated mathematical analysis, but we will not need to tackle it, for it has been done for us by the best of the world's mathematical brains, and all we need to do is to select one of a small number of standard sets of curves. Even this is not absolutely necessary, as will be seen later on.

Calculating Curves. First Principle.

The focal lengths of the lenses of crown and flint glass respectively, which form an achromatic pair, must be proportional to their dispersive powers.

The makers of optical glass give an analysis of each piece supplied, setting forth its refractive index (μ), its dispersion (Δ), the reciprocal of its dispersive power (V), and some other figures with which we need not concern ourselves. For example:

No.	Kind of Glass.	Ref.ⁿ Index for D.	Medium Dispersion C—F.	$V = \frac{\mu - 1}{\Delta}$	Partial Dispersion. C—D.	D—F.	F—G.	Sp. Gravity.
A605	Hard crown	1.5175	0.00856	60.5	0.00252	0.00604	0.00484	2.48
A569	Soft crown	1.5152	0.00906	56.9	0.00264	0.00642	0.00517	2.55
A458	Light flint	1.5472	0.01196	45.8	0.00348	0.00848	0.00707	2.93
A370	Dense flint.....	1.6124	0.01650	37.0	0.00474	0.01176	0.01030	3.57
A360	Dense flint.....	1.6225	0.01729	36.0	0.00493	0.01236	0.01054	3.66
A337	Extra dense flint	1.6469	0.01917	33.7	0.00541	0.01376	0.01170	3.88

The above is extracted from the lists of Chance Bros., of Birmingham, who will give with every piece purchased from them the correct figures corresponding to those in the columns herewith. The columns headed "Ref. Index for D," "Medium Dispersion" and

$$V = \frac{\mu - 1}{\Delta}$$

are the only ones with which we need concern ourselves. The letters C, D, F, etc., refer to the dark lines in the solar spectrum which are designated by these letters, and "Dispersion C—F" means that the figure given in this column is the dispersion between the C and F lines of the spectrum. When we use these figures in calculating an achromatic lens, in the finished lens the solar spectrum will be folded back upon itself so as to *bring these lines together.* If we look at a map of the spectrum we will see that the C line is in the red, and the F line in the blue-green. Consequently, when so folded together, complementary colours are combined, and the resulting light is white or colourless (achromatic), except that the violet end of the spectrum extends further beyond F than the red does beyond C. In fact, the spectrum is more "dispersed" at the blue end. This discrepancy, known as "irrationality," causes a little of the violet light to be left outside the correction, forming what is known as the "secondary spectrum." The result is that a slight purple fringe surrounds the images of every acromatic telescope, a fault which can only be remedied by the use of a triple lens and special kinds of glass. Such a triplet lens is known as an "apochromatic," and is an article of very great expense. We are here, however, only concerned with the doublet achromatic, and the amateur who succeeds in making a good one has reason to congratulate himself that he has done very well indeed.

In planning an object-glass, the first thing to be considered is its *focal length.* For clearness it will be well to take an actual example which has been worked, and show how it was done. I therefore take a 5-in. which I made a few years ago from "optical plate" crown and Chance's dense flint. The figures as supplied by the makers were as follows :—

Optical plate—

$\mu = 1.5195.$ $\Delta = 0.00906.$ $V = 57.33.$

Dense flint—

$\mu = 1.6230.$ $\Delta = 0.01730.$ $V = 36.0.$

The dispersions of the glasses are found in the column headed "Dispersion," but what we requireto work on are thedispersive *powers.* These are found by dividing $\mu - 1$, or the figure in the column headed "Refractive Index for D," less by unity, by the figure in the dispersion column. But we need not even trouble to do this, for the figure in the column headed V is the reciprocal of this quotient, and we can use the V figure, if we remember that it is a *reciprocal*, and that consequently the proportion is *inverse.*

Here, for example, we have for crown V=57.33, and for flint V=36. Therefore, a lens composed of a convex crown of 36-in. focus and a concave flint of 57.33-in. focus will be achromatic *if composed of these two glasses.* But its focal length will probably not be what we require. Let us see what it *will* be.

The formula for focal length of a series of lenses in contact is—

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3}, \text{ etc.}$$

if all are positive or all negative. If some are one and some the other, it becomes—

$$\frac{1}{F} = \frac{1}{f_1} - \frac{1}{f_2} + \frac{1}{f_3}, \text{ etc.}$$

the concaves being negative and the convexes positive. If there is a space d between any of them, then

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2 - d}. \text{ etc.}$$

Now we see from the above how to obtain the focal length of our combination of a convex of 36 in. and a concave of 57.33.

$$\frac{1}{36} = .02777$$

$$\frac{1}{57.33} = .01744$$

$$\text{Difference} = .01033$$

$$\frac{1}{.01033} = 96.8$$

Therefore a lens composed as above of a convex 36 in. focus and a concave 57.33 in. focus will have a combined focus of 96.8 in.

Or thus :—

$$\frac{1}{36} - \frac{1}{57.33} = \frac{57.33 - 36}{57.33 \times 36} = \frac{21.33}{2063.88}$$

$$\text{Reciprocal of this} = \frac{2063.88}{21.33} = 97.2$$

This would answer well for a 6½ in. object-glass, but would be too long for a 5 in., for which we want about 75 in. But a simple sum in proportion will now give us the figures for this. We may call 96.8 in. 97 in. as more exact :—

97 : 75 :: 36 : 27.8 crown focus.
97 : 75 :: 57.33 : 44.22 flint focus.

We have now reached the conclusion of the *first step* in our calculation of curves, for we have ascertained that our *convex crown* lens must be 27.8 in. focus, and our *concave flint* 44.22 in. focus, in order that the focal length of the combination may be 75 in. We have also ascertained that this combination will be *achromatic* if made of the glasses whose μ, Δ, and V figures are those above given.

× follows from this that focal length of combination equals product of the two V's divided by their difference
where fcr = Vfl in. & ffl = Vcr in.

In Summary.—To produce an achromatic combination from two glasses taken from makers' lists, look to the column headed V, and let the focal lengths of the two lenses be inversely proportional to the figures opposite the glasses in the column under V.

N.B.—It may here be noted that the heading of the fifth column in the table is nearly always misprinted. It should be as above stated

$$V = \frac{\mu - 1.}{\Delta}$$

Probably "printers' devils" do not understand Greek letters. The actual dispersive powers would be expressed by

$$\frac{\Delta}{\mu - 1}$$

But, as a glance at the example from Chance's list will show this quantity would be a very small fraction, whereas its reciprocal, or

$$\frac{\mu - 1}{\Delta},$$

is an integral number somewhere between 30 and 60, and therefore more convenient to work with, but the proportion is inverse instead of direct. This, however, is no drawback in practice once it is recognised.

Second Principle.

Having ascertained the focal lengths required, we now proceed to inquire what *curves* we must work the surfaces of our two lenses to, in order to obtain these *focal lengths*. And we also want to know how to provide for the elimination of spherical aberration. We have already stated that the latter condition is secured by adopting one or other of a few standard sets of curves which are well-known and used by all opticians. In 1915 the National Physical Laboratory published a book of data for object-glass construction containing suitable curves for all of Chance Bros'. glasses (Harrison & Sons, St. Martin's Lane, W.C.). The worker has therefore only to make his selection.

The most usual set of curves is as follows :—

Crown lens : Radii of surfaces as 2 : 3.

Flint lens : One surface fits one surface of crown, or is a *slightly* deeper curve. The other surface is either plane or a concave or convex of long radius (*i.e.*, very nearly plane).

These are the ratios of the curves to each other. Now, what must the curves be ?

Beginning with the crown lens, its focus is to be 27.8 ins.

The formula connecting curvature with focal length is :—

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right).$$

But in the present case

$$\frac{r_1}{r_2} = \frac{2}{3}.$$

Therefore the formula becomes

$$\frac{1}{f} = (\mu - 1)\frac{5}{2r_2} = \frac{5(\mu - 1)}{2r_2}.$$

Substituting for f and μ their values, which we know (27.8 and 1.5195) :—

$$\frac{1}{27.8} = \frac{.5195 \times 5}{2r_2} = \frac{2.5975}{2r_2}$$

$$\therefore 27.8 = \frac{2r_2}{2.5975} \quad \therefore \quad 2r_2 = 27.8 \times 2.5975 = 72.21$$

$$\therefore \quad r^2 = 36.1 \text{ in.}$$

But r_1 is $\frac{2}{3}$ of r_2, therefore $r_1 = 24.06$ in.

Curves for crown, therefore are respectively 36.1 in. and 24.06 in.

For the flint we proceed in the same way. But we have one of its curves already, as it is to fit the crown. (This is not necessary, but is very convenient and labour-saving, as crown and flint may be made to grind each other). Now which surface of the crown is the flint to fit ? If we make it to fit the deeper side, we shall find that with a flint of such a high dispersion as that before us ($\Delta = 0.0173$), the other surface will have to be *convex* in order to get the requisite focal length. This convex fourth surface would make an excellent lens with a large flat field, and would be particularly useful for photography. But convex surfaces are difficult to figure, and at present we desire to simplify the making of our lens as far as possible. We therefore place the shallower curve of the crown next the flint, as is done in nine object-glasses out of ten. The first surface of the flint is therefore to be 36 in. radius. Now to find the other. Formula as before :—

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right). \quad \text{Substituting}$$

$$\frac{1}{44.22} = .623\left(\frac{1}{r} + \frac{1}{36}\right) = \frac{.623(36 + r)}{36r}$$

$$\therefore 36r = 44.22 \times .623\ (36 + r) = 27.55\ (36 + r)$$

$$\therefore 36r = 991.8 + 27.55\, r^*$$

$$\therefore 8.45\, r = 991.8$$

$$\therefore r = 117.3 \text{ in.}$$

Radius of fourth surface is therefore 117.3 in. Now we can write down the data in full for our 5 in. object-glass.

---

* If this figure is *greater* than that on the left of the equation the coefficient of r at the next step will become negative. This would mean a curve *opposite* to that of the other surface, *i.e.*, in this case *convex*. If the figures are equal it will be plane.

Crown lens { 1st surface, 24 in. / 2nd surface, 36 in. } convex

Flint lens { 3rd surface, 36 in. / 4th surface, 117 in. } concave

f crown = 27.8 in. / f flint = 44.22 in. } F combined = 75 in.

We have neglected the decimals in the radii because the calculated values of 24.06 and 36.1 are so close to integers that practical working could hardly take account of the differences; and also for the following reason, viz :—

The above formulae are *not exact*, except for the theoretical case of a lens with no thickness. For such lenses as we are dealing with, where the focal length is about 100 times the thickness, the error introduced by neglecting the thickness is very small. Its effect will be to make the finished lens slightly over-corrected for colour. Opticians often take no notice of this at all, and it is for this reason that over-corrected lenses are very common, and observers not versed in technical optics imagine that the blue blotch surrounding bright stars is a defect inherent in the refracting telescope. As a fact, the secondary colour ought not to be *blue*, but purple, and ought to be quite unobtrusive at focus. If it is blue *at focus*, the lens is over-corrected—still more if it is green. *Outside* focus the image should have a green fringe, and *inside* focus a purple one. Any other colours indicate wrong correction. Some opticians, after calculating the curves, make the crown curves a little deeper, and the flint just a shade shallower than the formula indicates. As a rough rule of thumb compensation for thickness, to make the first surface of the crown deeper by about 3 per cent. and the back of flint shallower by about 5 per cent. of its radius will bring things very nearly right. In a $5\frac{1}{4}$ in. object-glass made of the same glasses as above I compensated for thickness by making the back curve of the flint longer by not quite 10 per cent., 127 in. instead ot 117 in., while crown was worked as computed. The result was a practically perfec correction, but the focal length of the finished lens, which was designed to be 73 in., came out 69.5 in. This did not matter, and the lens was a most successful job. If it is important to work close to a given focal length, the compensation may be divided between the crown and flint, but the crown should have the most of it, if not all. The flatter the back curve of flint the less of the correction should be given the flint. If plano it should have none, and the front surface of crown should have all. If it be desired to correct for thickness in the *computation* we proceed as follows :—

Formula for focal length of a lens of thickness, t :—

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) - \frac{t(\mu - 1)^2}{\mu r^1 r_2}$$

In a plano—whether concave or convex—r_2 is infinite :

$$\therefore \frac{t(\mu - 1)^2}{\mu r_1 r_2} = 0,$$

having an infinite factor in its denominator. Thickness, therefore, makes *no difference* to a *plano* lens. And as the flint of an object-glass is usually very nearly plano-concave, r^2 is very long and the denominator of the fraction

$$\frac{t(\mu - 1)^2}{\mu r_1 r_2}$$

is very large, and the value of the fraction therefore very small. Consequently we need only consider the crown lens, in compensating for thickness, if the flint is plano-concave or nearly so. But if the correction is not introduced in the computation, it will be necessary to divide it between the lenses in any rule-of-thumb process, if we wish to avoid disturbing the computed focal length of the combination.

In a double-concave, as r is negative, the formula becomes—

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) + \frac{t(\mu - 1)^2}{\mu r_1 r_2}$$

The correction is therefore additive and the focus is shorter (*i.e.*, the lens is stronger) than a thin lens.

Neglecting to compensate for thickness, therefore, makes the flint lens too strong and the crown too weak; therefore the colour correction is too great.

Before proceeding to practical working it may be useful to give one or two more examples.

For the $5\frac{1}{4}$-in. object-glass mentioned above the curves were computed as follows :—

Same glasses as before—viz., Plate crown and Chance's heavy flint.

Crown $\mu = 1.5195$. $\Delta = .00906$. $V = 57.33$
Flint $\mu = 1.62324$. $\Delta = .01730$. $V = 36.0$

1st surface $r = 23.4$in. } Convex.
2nd ,, $r = 35.1$in. }
3rd ,, $r = 35.0$in. } Concave.
4th ,, $r = 116.6$in. }

(1st surface 22in. would have brought this nearly right).

Crown $f = 27$in.
Flint $f = 43.14$in.
Combination $F = 72$in.

In working this, as above stated, to avoid over-correction, the back curve of flint was worked to 127 ins. instead of 116.6 ins:, and the focal length came out 69.5 ins., instead of 73 ins. Next to the set of curves having crown radii 2 : 3, the most usual is one with an equiconvex crown. This has, as a recommendation to the optician, the advantage that it requires only one set of tools for the two surfaces of the crown. A 3-in. lens of this type, by Sir Howard Grubb, in my possession, has the two surfaces of the crown lens so exactly alike that reversing it makes practically no difference to the perfection of the images.

The calculation of the curves also is somewhat simplified by having $r_1 = r_2$ so that

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \text{ becomes}$$

$$\frac{1}{f} = (\mu - 1)\frac{2}{r}$$

$$\text{or } = \frac{2(\mu - 1)}{r} \quad \therefore f = \frac{r}{2(\mu - 1)}$$

If $\mu = 1.5$, as it very nearly is in a soft crown, $2(\mu - 1) = 2 \times 0.5 = 1$, and the formula becomes merely $f = r$.

In general an equiconvex crown lens has a focal length *nearly* equal to the radius of either surface.

As an example let us calculate the above $5\frac{1}{4}$-in. lens, with an equiconvex crown. As before :—

Crown : $\mu = 1.5175$. $\Delta = .00906$. $V = 57.33$
Flint : $\mu = 1.623$. $\Delta = .01730$. $V = 36$

Crown, focus 27in.
Flint, focus 43.14in.
F (combination) = 73in.

For the crown—

$$\frac{1}{f} = (\mu - 1)\frac{2}{r} = \frac{2(\mu - 1)}{r}$$

$\therefore r = 2f(\mu - 1) = 2 \times 27 \times .5195 = 28.953$ in.

For the flint, one radius is 28.053 in.

$$\therefore \frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r^2}\right) \text{ becomes}$$

$$\frac{1}{43.14} = .623\left(\frac{1}{28.05} + \frac{1}{r}\right) = \frac{.623\,(r + 28.05)}{28.05\,r}$$

$$\therefore 28.05\,r = 43.14 \times .623\,(r + 28.05)$$
$$= 26.876\,(r + 28.05)$$
$$= 26.876\,r + 753.872$$
$$\therefore 1.174\,r = 753.872$$
$$\therefore r = 643 \text{ in.} = 53 \text{ ft. } 7 \text{ in.}$$

Therefore we have—
1st, 2nd, and 3rd surfaces, 28.05 in.
4th surface, 643 in.

Messrs. Chance Bros., of Birmingham, the well-known makers of optical glass, have lately added to their lists a crown and flint designed to give perfect correction of both chromatic and spherical aberration with *three curved surfaces of equal radii, and one plane one*, thus eliminating all but the most simple calculation for curves.

CHAPTER IX.

Practical.—Shaping and Grinding.

It will not be necessary to recapitulate the processes of coarse and fine grinding, which have already been described in dealing with speculum making. Everyone who has made a concave mirror is already familiar with the production of con-

cave and convex spherical surfaces by grinding two equal plane discs of glass upon each other. The same process which produces the shallow curves of telescopic specula need only be carried a little further to produce the deeper curves of an object glass. There is only one important difference—viz., that now we have to produce curved surfaces *on both sides* of a disc of glass, and these surfaces must be correctly centred with respect to each other. In other words, the edge of the lens must be exactly the *same thickness all round*. To secure this we require a pair of *micrometer callipers*. The ordinary callipers are not at all delicate enough for the extreme accuracy required. An error of 1-1,000 inch in the thickness of the edge will produce a most deleterious effect on the images produced by the finished lens.

The optical glass we require is sold either in discs or in square slabs. In the latter form it is considerably cheaper, but we have the trouble of cutting out the discs. This operation is not so difficult as it looks. The corners of a square slab of glass are quite easily sawn off with a piece of hoop-iron and a little No. 80 or 120 carborundum and water. The saw-cut is begun on one side and carried nearly half-way through, then begun again on the other side, and when the cuts have come near enough the corner is gripped in the vice and broken off. In this way the square is made an octagon. The angles of the octagon can then be further blunted with the carborundum wheel or grindstone, and finally the piece is cemented with pitch to a pair of wooden handles, mounted in the lathe and edged circular, and reduced to the required diameter in the same way in which the disc for a mirror is edged. (See page 16.) Two discs, the crown and flint, will, of course, be prepared, and these must be of *absolutely exactly* the same diameter. It is a good plan to cement them together and edge both at the one operation. But care is necessary not to damage them in parting them again. Also, the edges should be bevelled as a precaution against chipping by accidental blows. Two or three discs of ordinary plate glass $\frac{3}{4}$ in. thick or thereabouts should be edged also to the same diameter, to serve as tools.

If it has been decided that the second and third surfaces, being of the same radius, shall be made to grind each other, thus saving one whole operation of rough and fine grinding, we now cement the crown disc to a thick disc of wood, as we would the glass tool for a mirror, but with this difference, that the block should be of considerably smaller diameter than the glass, about two-thirds of it, and it is provided with a disc of sheet-iron of a diameter a little greater than the glass, which is screwed to the wooden disc concentrically for attachment to the barrel, the arrangement being similar to Fig. II. in the chapter on speculum grinding. The glass is, of course, cemented with pitch and the sheet-iron is attached to the top of the now familiar barrel by means of screws. The object of the arrangement is twofold. The crown disc is not very thick, and if attached to a bed of pitch covering its whole surface would infallibly be flexured. And later on, when the other side of

the crown is being ground, it will be necessary to have *room on both sides* of it to admit the micrometer callipers to gauge the thickness of the edge.

We are now ready to commence operations, and having provided the flint disc with a wooden handle, as we do a mirror, and placed a basin of water and a handful of cotton-wool handy on the work-bench, we proceed to arm the discs with a sprinkling of No. 80 carborundum, dip the flint in the water, lay it on the crown, and grind with the mirror-maker's threefold motion. It is to be noted that the handle by which the flint is held should be carefully centred. This is not absolutely necessary in grinding a mirror, but essential in making a lens whose two surfaces have to work with each other. About two or three hours, according to the size of the disc, will probably suffice to bring the curve near the required depth. As the grinding progresses the curve is checked from time to time, as in the case of a mirror,

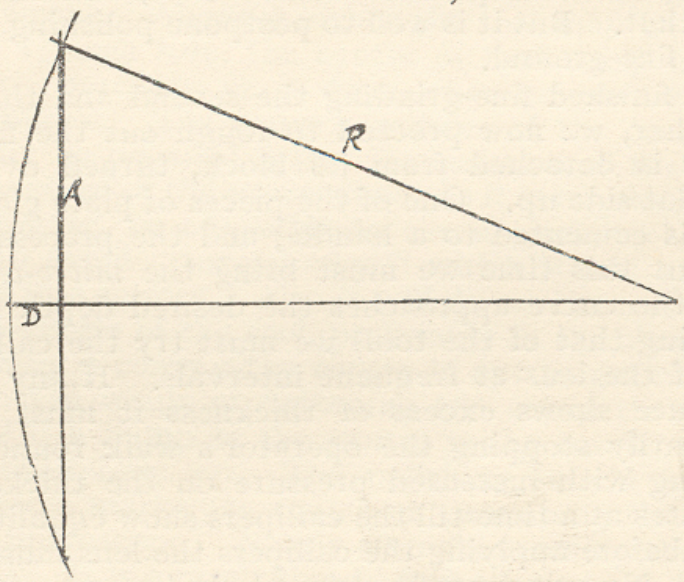


FIG. 19.—The radius $R = \frac{A^2 + D^2}{2D}$

by wetting the concave surface and testing it with a light. (See p. 18.

It is necessary to stop the rough grinding while the curve is still a foot or more longer in radius than we require. Carefully clean the discs and barrel of all trace of the rough carborundum, throw away the cotton-wool and water in the basin, and get a fresh lot, and proceed to the next carborundum grade, 220. With this the curve is brought very nearly to the exact depth required. To gauge its progress more exactly than with the candle flame, we now use the modification of Foucault's pin-hole lamp, which we used for testing mirrors at the same stage. (See page 18.) Opticians use a spherometer to read the curve of spherical surfaces. This is a small instrument with three feet, either pointed or ball-tipped, the three occupying the angles of an equilateral triangle. In the centre is a fine micrometer screw, with a point which can be screwed down to touch the surface on which the feet rest. The radius of the curve is obtained from its reading, as shown in the figure (Fig. 19).

The reading of the micrometer screw gives d, and a is the distance from the screw point to each foot. The spherometer is an expensive little instrument if accurately made, and the method described above of obtaining the radius of a concave curve is just as accurate in practice, if not more so. To measure a convex we measure the concave tool which ground it, and as the fit of the two at the end of fine grinding is very exact the method is quite satisfactory. The directions for fine grinding given in the section on mirror-working are in no respect different from the methods to be used with a lens, and they need not be here repeated. The only difference is that, as the convex tool in this case is the crown lens itself, it is not advisable to use it to form the pitch tool or for polishing the corresponding concave. Any old glass tool of approximately the same curve and size can be used, or, failing a suitable one, a disc of hard wood can be turned up to near the curve, and the pitch tool formed on that. But it is well to postpone polishing any surface till all are fine-ground.

Having finished fine-grinding the second and third surfaces on each other, we now proceed to rough out the first surface. The crown is detached from its block, turned over, and re-cemented flat side up. One of the pieces of plate glass prepared for a tool is cemented to a handle, and the process goes on as before. But this time we must bring the *micro-callipers* into play. As the curve approaches the desired depth (ascertained by measuring that of the tool) we must try the callipers round the edge of the lens at frequent intervals. If any part of the circumference shows excess of thickness it must be reduced by temporarily stopping the operator's walk round the barrel and working with increased pressure on the thickest part for a few minutes at a time till the callipers show equality all round. Of course, before applying the callipers the lens must be washed and dried. No grit must be present, and a wet surface is very undesirable.

As the *thickness* of the lens enters into the formula for focal length, it will be necessary to pay attention to this point. $\frac{1}{2}$-inch is a convenient thickness for a 5 in. to 6 in. lens (crown). If the slab to begin with is just a little more than this, it will come very nearly right when finished. If not, perhaps the simplest way will be to compute the curves at first for a thickness a little less than that of the slab. Otherwise it may be necessary to grind with very short strokes, in order to prevent the curve reaching the desired depth before the thickness is sufficiently reduced, which would waste a lot of time and labour.

When the fine-grinding of the first surface is complete, we turn to the fourth surface. As this is a shallow curve, working it resembles in every respect the making of a mirror, except that the micro-callipers must be busy checking the exact equality of thickness all round the edge. The handle (cemented to the centre of the third surface) must be carefully centred. Grip it in a three-jaw chuck in the lathe, and rotate it and the disc while the pitch is still soft, and correct any lack of truth in its running by pressure in the direction required. It will be nearly

impossible to keep the third and fourth surfaces truly centred with respect to each other if this handle is not in the centre of its disc. When completed, or better, just before the last stage or two of fine-grinding, it will be well to see that the bevel placed on both discs is not ground entirely off. If it is it should be restored, or an ugly chip may result from any slight accidental jar.

Polishing.

Once more the mirror-maker finds himself on familiar ground, with some differences. The pitch polishing tool is formed, just as in the case of a mirror. It is, however, less necessary to be careful about the facetting. For sizes of 4 inches and under it is not necessary to facet at all, or two channels at right angles to each other, dividing the tool into four unequal parts will be sufficient. Above 5 inches the tool may be divided into squares of $1\frac{1}{4}$ inch side, the centre of tool being in the corner of a square, precisely as is done when preparing a polishing tool for a mirror. The convex surfaces of the crown lens may conveniently be polished first. No question of their figure can arise at this stage of the proceedings, as it is impossible to test it. It will, however, be advisable to use a pitch tool well on the hard side to avoid " turned edge," which is just as formidable in a lens as in a mirror. Also it will do no harm to cut away a little of the centre of the tool, preferably in the shape of a star ; as in polishing a convex the centre is apt to get more than its share, with the result of flattening the curve there. It is no harm at all if a hump in the centre is the result, as it is very easily removed later on. The polishing should be continued till no abrasive marks are visible on examining the edge of the lens with a microscope. Nearly all makers scamp their polishing more or less. It is a rare thing to find a lens, even by the great masters of the art, one or more surfaces of which do not show, when examined with a low power on the miscroscope, thousands of tiny abrasive pits. Each of these is in practice a minute opaque spot, and the presence of thousands of them has two results, both bad for the performance of the lens. It reduces the transparency, and consequently the light-grasp. And it introduces diffraction effects which scatter light and illuminate the back-ground of the field of view. The crown lens may be polished either face up or face down. Face down is probably preferable, as the small handle cemented to the glass for holding by, is more easily detached and refixed without danger, than the block underneath would be, and there is less risk of flexure. It must always be borne in mind that the crown lens is the thinner of the two, and not half the thickness, relative to its diameter, that a mirror would have. Fortunately, flexure must be much greater, to affect perceptibly the performance, in a lens than in a mirror. The reason is that if a lens is flexured, the two sides are bent *opposite ways*. Consequently the flexure of one side compensates that of the other. Sir H. Grubb has shown that in the theoretical case of a lens with no thickness, flexure, however great, would have no effect, for the compensation of one

side by the other would be complete. As our lens, however, must have a thickness we must see that flexure is avoided as far as possible.

Having polished the convex surfaces, we now proceed to the more familiar task of polishing the concaves. The third surface, the deeper concave, should be done first. Its figure can be roughly checked by the shadow test, though, owing to its short radius, it is impossible to test it with delicacy because the image of the pin-hole must be thrown far enough from the optical axis to distort the shadow very appreciably if it is to be brought within reach of examination. But it can be tested well enough to ascertain that its figure does not depart very markedly from a sphere. The fourth surface can be polished and figured usually just like a mirror. But we need not strive after any definite figure at present. It will suffice to see that it does not become a deep hyperbola. It is best to have it somewhere near a sphere. If it should by chance turn out to be a pronounced oblate spheroid, let it remain so, as the final correction will be all the easier. But do not tolerate any irregularities. Humps or hollows in the centre, or a turned down edge should be eliminated as carefully as from a mirror, especially the hollows.

CHAPTER X.

Testing and Figuring.

When the polish of the four surfaces is complete the lens can be assembled and tested for focal length. If the curves have been worked accurately as computed, this should come out very close to the computed focus. But if thickness was not taken into account in computing, and was compensated for afterwards by rule of thumb, we must expect the actual focus to be shorter, probably by some inches.

We can also test for performance, if we have a cell ready in which to mount the lens. If not, we must wait till this is made. This is a job for the lathe and the brass-finisher, but the amateur who is capable of constructing his own object-glass will certainly not be beaten by the cell.

But when assembled and mounted we must not expect the lens to be ready for use in the telescope. In fact, the hardest part of the job is still before us. The set of curves chosen was, to be sure, one of those computed to correct spherical aberration. But it is a thousand to one that it does not. And for a very simple reason. The tables laboriously computed to remove spherical aberration all assume that the curves are truly spherical. This, as a matter of fact, they never are, except by accident. We can figure concave surfaces to any curve our skill is equal to. But of the figure of our two convex surfaces we know nothing at all. It may be anything, ellipse, sphere, parabola, or hyperbola, or a mixture of all four. All we can do is to try the lens and figure one or more of its surfaces according to what we see. And, fortunately, it is possible to correct the errors of the sur-

faces we cannot test by figuring one of the surfaces which we can test. If there is an error in the convex lens which we cannot remove it is possible to compensate it. For example, if the centre of the convex lens is too flat, making the focal length of the corresponding part of the object-glass too long, we can compensate this by making an equal area of the centre of the concave lens also too flat. Or, if the whole lens, though regular in correction, proves under-corrected for spherical aberration (*i.e.*, the focal length becomes greater as we pass from margin to centre) we can compensate it by figuring the back of the flint lens to a more or less pronounced oblate spheroid. If, on the other hand, the whole lens is over-corrected, we figure the back curve to a hyperboloid. The under-corrected condition is far more likely to occur, and it is for this reason that it is well to leave the preliminary figure of the fourth surface a sphere or an oblate spheroid. It is very easy to convert it into a hyper-

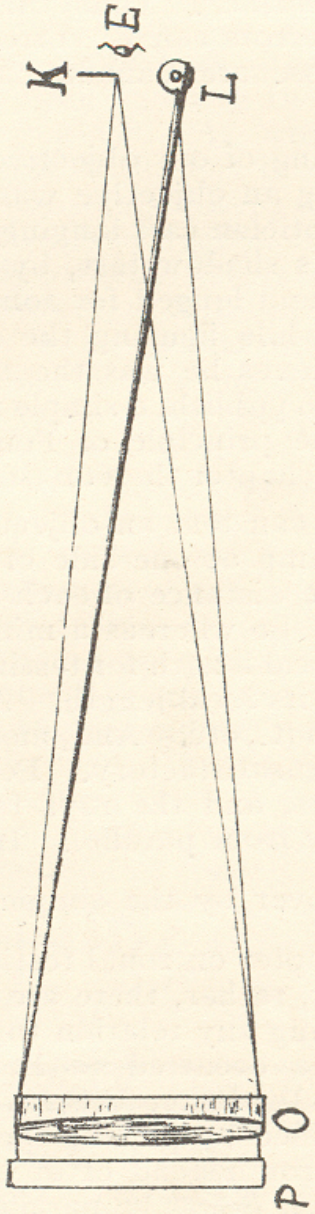


FIG. 20.

bola if necessary. If the errors found on trying the lens are of large amount it may be necessary to figure all four surfaces to eliminate them. But if we can ascertain that an observed error is due to some one surface, it will of course be best to refigure the offending surface itself. How, then, can the offender be located? This is where the advantage of having as few convex surfaces as possible comes in. When we have two concave surfaces, we can ascertain by direct inspection with Foucault's lamp and knife-edge if either of these is at fault. If not, then the fault must be in one or other of the convexes. To ascertain which of them is at fault is easy with the set of curves we have been working—viz., one having the second and third surfaces in contact. If a transparent liquid having nearly the same refractive index as glass be placed between these surfaces, they are optically abolished, and the lens behaves as if it were a solid one having only two surfaces. Therefore, if the defect be in the second surface it vanishes. If it still is there, it can only be in the first surface. Thus the offending surface is tracked down and its errors can be corrected *in situ*. Liquids suitable for the purpose are Canada balsam, castor oil, and glycerine.

Now as to the testing of our objective. Till quite recently the only way of testing an objective was by actually trying it on a star. Many an optician cast longing looks on the ease and simplicity of Foucault's shadow test, by which mirrors can be figured so accurately, and longed for something equally simple for guiding his hand while figuring the surfaces of an object-glass. The writer believes he was the first to devise, and he certainly was the first to publish, a simple means to this desirable end. Let us recall the principle of Foucault's apparatus, referring to the previous chapter thereon (see Fig. 6, p. 23).

It is clear that we can test an objective as there described only by putting the lamp at one side of it and the knife-edge at the other. Also the distance of each from the lens must be twice its focal length. So whereas a mirror requires a straight line of twice its solar focal length for testing it in, an object-glass will require four times its focal length. A 4-in. would theretore require 20 ft., a 5-in. 25 ft., etc. And, moreover, when so tested, the results would be unsatisfactory. For an objective is corrected for parallel rays, and the rays from a point two focal lengths distant are far from parallel. In the case of a mirror this objection is got over by the simple little formula $A=\frac{r^2}{R}$, as explained in the chapter on zonal testing. But in an object-glass there is no R, or, rather, there are four R's, all different, and none of them having any relation to the focal length of the double lens. ~~The idea occurred to Professor Pullan, of the Alabama Polytechnic Institute, U.S.A., that~~ the testing of a mirror ~~could~~ can be simplified by placing the Foucault lamp at the solar focus of the mirror instead of at centre of curvature, so that the returning beam ~~would~~ will be parallel, receiving this parallel beam on a plane mirror which returns it to the concave, from

Prof. Ritchey gives in his book on the reflector, a method by which

which it is again returned convergent to the eye and the knife-edge. In this way the necessity for using the $A = \frac{r^2}{R}$ formula disappears and the surface of a truly parabolic mirror presents the easily identified flat appearance which in Foucault's method characterises the sphere. But the arrangements needed are awkward and complicated, and the method is not likely to supersede Foucault's. But in examining Professor ~~Eulan~~'s Ritchey apparatus it flashed across my mind that this was just what was wanted as a workshop method for testing object-glasses. It did not take many minutes to set up the apparatus. A plane mirror in front of the object-glass, as close to the first surface as possible, Foucault's lamp and knife-edge at the solar focus of the lens, and the outfit is complete, as in the figure. Fig. 20.

The light from the pinhole-lamp, L, at the solar focus of the lens, O, falls on the lens, and, after passing through it, issues as a parallel beam. As a parallel beam it falls normally on the ~~plain~~ plane mirror, P. It returns from the mirror still parallel, re-enters the object-glass parallel, as a beam from a star would, and is by it converged back again to the solar focus, where it forms an image of the pin-hole. As before in the mirror test, a slight *ecart* of the lamp to the left diverts the image to the right sufficiently to enable an eyepiece, or the eye itself, to receive it. If the objective is perfectly corrected, the divergent beam becomes parallel without aberration, and the parallel beam again becomes convergent without aberration, and when the knife-edge is made to cut across the beam exactly at its focus, the eye just behind it sees the illuminated lens darken evenly all over, with the flat appearance of a truly spherical mirror under Foucault's test. But if the object-glass under test has defects in its correction, every such defect is doubled ~~in its effect~~, because the light passes through the lens twice. The chromatic correction, as well as the spherical, is tested by this useful device, by examining the image with an eyepiece. On pushing the eyepiece inside, or drawing it outside, focus, the colours of the secondary spectrum are seen, as when the image of a star is examined in the same way in the telescope. Only in the apparatus the secondary spectrum, like all other outstanding defects, is doubled. In optical apparatus the name of " collimating lens " is given to a lens whose office is to render a divergent beam parallel before it enters an objective. We have therefore given to this method of testing the name of the Auto-collimation Test, because the objective under test acts as its own collimator. The method was known to Alvan Clark as early as 1873, but was kept a close trade secret

CHAPTER XI.

TESTING AND FIGURING—*continued.*

Now let us suppose that our objective is under-corrected for spherical aberration, as it is almost certain to be ; because, in the absence of any check on the figure of the convex surfaces, these surfaces get almost invariably too much polishing in the centre, with the result that the curve is too flat there and the

central focus too long. This will reveal itself in the auto-collimation test as a forward bulge or hump towards the observer. Whereas, if the lens be over-corrected, it will look hollow in the centre, bulging away from the observer. If the under-correction is not great, it may be remedied by working the back of the flint lens to a similar hump, making it an oblate spheroid, in fact. If too great for this, we must find which surface is at fault and try to remove the flat centre by working with a tool with the centre more or less cut away. If there is any uncertainty whether a visible defect is due to a hill or a hollow, the point can be cleared up by a very neat method given by Sir Howard Grubb in a paper in *Nature*. Rub the bare hand over the glass at the spot affected. The warmth communicated by the hand to the glass causes a slight bulge thereon. Now test again before it has time to cool. If the defect was due to a hill, it will be aggravated ; if to a hollow, it will temporarily disappear, and you can watch it come back again as the glass cools. A hollow must be treated by polishing with a tool which acts on the rest of the surface and leaves the hollow spot alone. The remedy for a hill is obvious.

Far more difficult to treat than hills and hollows is a turned-down edge, a defect which nearly all object-glasses by second-rate makers suffer from. It is indeed the *bete noire* of the optician always ready to show its objectionable presence on every surface polished with pitch. It is on account of the ever-present fear of turned edge that it is always advisable to keep pitch too hard rather than too soft. And one of the advantages of a slight admixture of beeswax in polishing pitch is that it greatly reduces its tendency to turn an edge. It is much easier to prevent turned edge than to cure it. Therefore, in polishing our surfaces we took care to use pitch on the hard side, and to finish our back surface if possible with a turned-up edge, as this will neutralise a possible turned-down one on another surface. But if, in spite of all, we find a turned-down edge showing in the auto-collimation test, we must polish at our convex surfaces with hard tools, and tools slightly less in diameter than the lens, till the defect is eliminated. It often happens that we get rid of it partly with much ease by working at one surface, but cannot get any further. The best plan then is to attack the other in the same way.

The operator who has the skill to figure a mirror successfully will have no real difficulty in overcoming the very analogous problems presented by an object-glass, especially as his task is rather simplified than complicated by the four surfaces, since he can, to a considerable extent, play off one against another. Another point in his favour is that the so often troublesome edge is cut off by the cell, so that he is not bound to be so particular that his curves should be exact up to the extreme edge. It may also be mentioned that the circle by which the light leaves the object-glass is necessarily smaller than that by which it enters it ; therefore, the cell flange may be a little deeper at the back than at the front without cutting down the clear aperture. A narrow defective zone on the back surface will

thus be kept out of action altogether. It will be seen also from the foregoing that, so far as the practical optician is concerned, the careful computing of curves to cure spherical aberration is waste of time. It is not too much to say that the operator who is skilled in figuring might safely undertake to produce a perfect object-glass with any set of curves whatever, provided chromatic aberration was corrected ; trusting to figuring alone to correct the spherical aberration. The writer has seen a 3-inch object-glass whose curves, if spherical, would only define with the convex lens in front, so manipulated that it would define perfectly with the flint lens leading, and not in its normal position. To such a length has skill in figuring been carried, that some amateur mirror and lens-makers can juggle with curves to an almost unlimited extent, producing at will any desired form of concave surface, from the most extreme oblate spheroid to the most extreme hyperboloid.

The detection of a turned edge when using the auto-collimator, is similar to the corresponding operation on a mirror, with one difference : When examining the image of the pin-hole with an eyepiece, it is the disc outside focus which shows a hairy edge in the case of an object-glass with a turned-down edge. With a mirror, it will be remembered, it was the disc inside focus which was affected. When testing an object-glass on a star in the telescope it will be the same ; and one of the first things to be noted will be the out-of-focus image of a bright star, outside focus. If this is circular and fairly sharp in outline, and its edge is slightly green in colour, a favourable judgment of the lens may be formed at once, as the commonest defect of an object-glass is not present. Inside focus the expanded disc should be similar to what it is outside, except that the margin should be slightly purple instead of green. If the lens is properly corrected for both spherical and chromatic aberration it will come sharply to focus exactly at the point where the purple disappears and the green appears, or *vice versa*. At this point the image in a good lens is very nearly colourless.

When, satisfied with our workshop tests, we come to try our objective on a star it will be necessary first to see that the lenses are an easy fit in the cell, and that the counter-cell is screwed home, but not tight. The lenses should rattle very slightly when shaken. Then the cell is screwed home into its object-end and a look taken at a bright star with a moderately high-power eyepiece, say, $\frac{1}{4}$ or $\frac{1}{3}$ inch. The first view will not be a good one, as the objective will be " out of square." The star will have a flare on one side. With the type of objective we have been making, to remedy this the side of the objective next the flare must be pushed in or the opposite side pushed out. Let the screws holding the object-end to the tube be loose enough to enable the end to move when moderate force is applied. Place a short piece of wood against the cell and tap it in the required direction with the wooden handle of a screwdriver or other convenient object. If the cell has pull-and-push screws, so much the better. When the image is as symmetrical as possible, put on the highest eyepiece you have, and focus

carefully, and note the appearance of the star-image. It should be a tiny, circular dot, surrounded by one or two very fine rings of light. If these rings are too numerous, or are thick and coarse, spherical aberration is not fully corrected. If they are thicker on one side of the image than the other the squaring is still defective, and the side of the objective next the thick part must be pushed in a little more. A slight amount of astigmatism is very often found in an objective when first tested, after all adjustments have been made as perfectly as possible. This shows itself by the image, a little out of focus, being not circular, but slightly oval, the major axis of the oval being one way inside focus, and at right angles to that outside focus. The cause of this is slight flexure, probably present in both lenses. To remedy this the lenses must be rotated on each other a little at a time until a position is found in which the defect vanishes or is reduced to the smallest possible amount. When this is found, the edges of the lenses must be marked so that they can always be placed with certainty in their right relative position. Some makers notch the edges and solder a pin into the cell to fit the notch, so that if removed for any purpose the lenses cannot be replaced except in the right way. Rarely indeed is a lens so perfect as to be quite indifferent to the positions of the components with respect to each other. If the oval images cannot be made to become circular in any position, one or other lens is seriously flexured, and it may be necessary to re-grind it. But this should not happen if proper care was taken in supporting the lenses correctly in the original working. If badly astigmatic, the image at focus will be a cross instead of a small disc or a point. For this the only remedy is to return to the last stages of fine-grinding, and use greater care.

If the image is irregular, the glass is at fault, and the matter must be referred to the maker.

CHAPTER XII.

The Flat or Diagonal Plane.

To produce a true plane is a much more difficult job than to produce a true curve. I trust readers will not be disappointed when I confess that I have never tackled it. But I have had a very good reason for not doing so. It is not worth while. Just as it is not worth while to try to make eyepieces, because good ones can be purchased for a very moderate price, which most pockets can afford, so it is not worth while to work planes. The worker who has made a 6-in. speculum can buy a suitable plane for from £1 to 30s. But there is a cheaper way still. Good polished plate glass has a surface so nearly optically plane that it is always possible out of a dozen pieces 2 ins. square or thereabouts to find one or two or even more with a surface as good as, or even better than, most worked flats. Some makers' glass has a much larger proportion of plane surface than that of others. The glass should be of a fair thickness, $\frac{5}{8}$ in. or $\frac{3}{4}$ in., as thinner glass bends in the process of polishing,

and consequently plane pieces are rare. We require two things (*a*) a means of testing the flatness of the surface, and (*b*) a means of cutting the selected piece to the elliptical shape which will be projected into a circle when viewed at an angle of 45°.

For testing a piece of glass three methods are available. The first, and best known, is Newton's colour-band test. This simply consists of placing a piece of glass, known to be a true plane, in contact with the piece to be tested, and viewing the interference colours seen when light is reflected from the surfaces in contact. The test-plate and glass are carefully cleaned and placed together. If the least gritting noise is heard they must be separated and cleaned more thoroughly. The worker's hands should be well washed and dried before touching the glasses, and if the hands are quite clean a light rub with the palm is the best way of getting rid of a trace of dust from the glass surfaces immediately before placing them in contact.

The best planes are those which show one uniform colour all over, when thus treated. Such are, however, very rare, and glasses may come much short of this and yet perform well in the telescope. We must, however, not trust to first impressions. Handling the glass produces disturbances of temperature in it which will quite alter the appearance of the colours seen on applying the test-plate. The proper way is to place the surfaces well in contact, and when a good show of colour is seen, by the reflected light from a window or the open sky, lay the glasses down on a clean folded cloth in the window, and leave them there for about half-an-hour. Then the colours seen will be a true index of the nature of the surface. But a finger laid on the upper surface will, by reason of the heat communicated to the glass, cause instant alteration of the colours below. Another way of testing is that described in the chapter on testing object-glasses under the name of the auto-collimation test. A plane mirror is there used to return a beam of light through the object-glass to be tested. Clearly the plane must be known to be true, in order to get a true test of the object-glass. Conversely, if we know that the object-glass is truly corrected, we may test the truth of the plane. For details and diagram we must refer the reader to a previous chapter, No. X.

If neither object-glass nor test-plate is available, we may get a fair test by trying the various pieces of glass on each other. If two pieces thus tested show the same or nearly the same colour all over, both must be good. If, as usually happens, the colour-bands are irregular, rotate first the upper glass and note what happens. Then rotate the lower. If one is defective and the other fairly good most of the irregularities in the bands will rotate with the more defective piece. In this way we pick out the best two or three pieces and try them on each other till we get a pair showing the minimum of irregularity in the colour-bands. By proceeding in this way till we get a pair of glasses which give a nearly perfect colour effect we may set aside one piece for a provisional test-plate, and the other for a flat. If the worker gets access to a source of really fine plate he may get

as far as 50 per cent. or more of his pieces perfect. The product of the St. Gobain factory was so fine that the writer has found as many as nine perfect pieces out of a dozen $1\frac{1}{2}$ in. $\times$ $2\frac{1}{2}$ in. rectangles.

Another way of testing a plane is by direct observation with a telescope. Lay the glass face up on a table at the open window, and get the sun, moon, or a star reflected in it. A small telescope is then directed at the object reflected and its image got into the field. A star is, of course, the best test, but the sun or moon is the easiest to find. If the image under a high power is equally sharp with the direct image, the plane is good. If the telescope be focussed on the direct image and then it is found that the reflected image, though good, is out of focus, the reflector is either slightly convex or slightly concave. If the eye-tube requires to be racked *out*, the reflected beam is divergent, and the reflector thereore convex. If it needs to be racked *in*, the reflector is concave. If the image is distorted, the reflector is irregular.

It is necessary to remark here that a piece of plate glass is never good on *both* sides. One side may be plane, or nearly so, but the other is sure to be very irregular. It is therefore well, after selecting a piece, to mark not only the piece selected, but the side of it selected. A letter or number may be scratched with a diamond in one corner, where it will be outside the ellipse when cut out.

Cutting Out a Plane.

The old plan was to get a cylindrical piece of wood, such as a broomstick, whose diameter was equal to the minor axis of the flat to be. This was cut to an angle of 45 deg. with a fine tenon saw. Two pieces of plane glass were cemented with their optical faces together, and the pieces of broomstick cemented to them in such a way that the one stick was the prolongation of the other, and when revolved in the lathe they rotated as one. The arrangement was mounted between lathe centres, and a strip of sheet iron, tinplate, or zinc used as described for edging a mirror, except that a much wider strip was required. This method would work all right if it could be kept cool. But the grinding produced so much heat that the pitch very soon softened and the pieces of glass, etc., parted company, the carborundum getting at the optical surfaces with disastrous effect. A very much quicker and more satisfactory way is as follows :—A piece of 3 in. square timber is cut into two lengths of about 9 ins. long, and the two bolted rigidly together to form one piece 6 ins. by 3 ins. To one is screwed a piece of wood just wide enough to fit between the parallel bars of the lathe bed. It lies longitudinally, forming a kind of keel to the 3 in. piece, so that when placed on the lathe bed, with the keel between the bars, the whole can be pushed longitudinally with a little effort, but it should have no play or looseness laterally. The other 3 in. piece (the upper one) is cut at one end to an angle

of 45 deg., this bevelled end facing the lathe mandrel. The back centre of the lathe is removed and the poppet head brought close up to the wooden contrivance and clamped there. Then the hand wheel screw is used to give the whole a slow motion towards the mandrel. This is the *carriage* for the flat while cutting. Now we require a piece of brass tube 3 ins. or 4 ins. long, inside diameter equal to minor axis of proposed flat, and ends turned up true and smooth. Plug one end with a turned plug of hard wood driven in tight and flush. Grip the plugged end in a 3 or 4 jaw chuck. This is our *cutter*. Now we get a piece of nice clean flat wood about 1 in. thick and 4 ins. square or thereabouts. Cut a hole in the middle a little larger than the diameter of the brass tube. Screw this to the 45 deg. face of the wooden carriage, with the hole so placed that the tube enters it when the carriage is pushed up.

When about to cut out a flat, we get a piece of common window glass, 4 ins. square, and cement it to this piece of wood with pitch. We also cement another piece of window glass over the optical face of the glass to be cut, to protect the surface from the abrasive. Finally, cement the back of the plane to the 4 in. piece of glass. While the pitch is still warm, set the carriage in place on the lathe and adjust the glass till its centre is opposite that of the cutter tube. When adjusted, lift off and fix the whole thing in the vice, with the glass horizontal, till cool.

When ready to cut, the wooden carriage is set in place in the lathe bed, a tin tray (lid of a biscuit-box) placed under the front of it to catch drip, the cutter-tube gripped in the chuck, and tested to see that it runs dead true. Then the hand-wheel screw is used to push the carriage up till the face of the glass just touches the cutter-tube.

Now we mix some 220 carborundum with plenty of water in a jam-pot, and place it handy. The lathe is put into a high speed, and rotated with the cutter just touching the glass, while carborundum and water is fed drop by drop on to the point of contact with a teaspoon. The right hand slowly screws up the wheel, keeping the glass just touching as the tube cuts it. Cutting is quite rapid. When advanced a little way in, the tube will hold a little pool of water and abrasive, the capacity of which continually increases, till, when well advanced, the tube can be filled nearly full. This charge lasts a long time. At last the end of the cutter-tube is completely entered into the glass. We must now proceed more cautiously, and when we can see through the end or side of the glass that the tube is right through the optical face, by about 1-10th inch, we may stop, and withdraw the carriage—glass and all—and lift it off the lathe.

A smart lateral blow with a wooden mallet will detach the glass from the wooden support. Now place the glass, face down, on your left hand, and give a light tap with a hammer in the middle of the back of the partly-cut ellipse. The whole piece drops out; wash all abrasive carefully away, hold it over the oil-stove till the pitch softens enough to remove the protect-

ing-glass from the optical face, and place the flat in a little spirits of turpentine till next day. This dissolves off the pitch, and it can then be wiped clean with a piece of soft paper, and finished with a linen rag. The final operation—a delicate one, and requiring care and a steady hand—is the lightly bevelling the sharp edge on a fine carborundum hone, with water. Beware of letting the optical surface touch the hone. If any projections or ragged corners are left on the back end of the flat on breaking it out of its matrix, these should be ground off on a carborundum wheel or grindstone, *before* removing the protecting glass from the face.

The actual cutting of a 1¼-in. flat takes about an hour. After cutting, cleaning, etc., it is well to test the surface again for truth of plane. Cutting out sometimes distorts a true plane a little. But it also sometimes improves one which is not quite true. It is therefore not always wise to reject pieces which are not quite perfect, as they may turn out better than expected. Of course, they may also turn out worse, but in using plate glass for making the flat, these chances must be taken; and "if at first you don't succeed, try, try, try again."

CHAPTER XIII.

Mounting Lenses and Mirrors.

The worker who has successfully finished an object-glass or mirror will, before he can use it, be obliged to provide it with a mount or "cell." An object-glass cannot even be tested accurately until fitted into its cell. It is therefore desirable to make this as soon as the preliminary polishing of the four surfaces is completed, before beginning the delicate work of figuring. The making of an object-glass cell will be a nice little exercise in brass-fitting, just the sort of job that the amateur lathe-man enjoys. We require first of all a suitable set of castings, unless the lens to be mounted is quite small, not over 2¼ in. aperature, in which case a piece cut from a heavy brass tube of the requisite size may be used, and will save the trouble of machining a rough

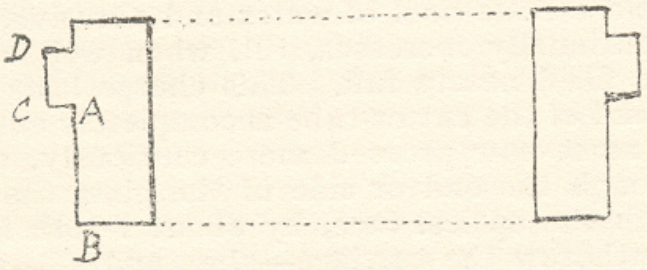


Fig. 21.—Sectional diagram of pattern for cell casting. If the portion AB be made deep enough, a ring turned off the lower part can be used for the counter-cell, saving a separate casting and pattern.

casting. But for a lens of any size castings are indispensable. If any quantity of brass scrap of fair quality is lying about, and

a friendly founder can be got to melt it down, it will save expense. We will require at least two castings, perhaps three. One of these will be for the body of the cell, a second for the counter-cell, or screw-ring which confines the lens in the cell, and the third for the "end," the piece which fits on to the telescope-tube and into which the cell screws. It is preferable, however, to make the pattern deep enough to enable us to turn off a ring from the bottom of the castings after the preliminary machining, and to use this for the counter-cell, saving the making of a very thin and flimsy pattern which would be liable to break or warp in the moulding. Fig. 21 shows the form of pattern required for the cell. By makng the portion AB a little deeper than shown there will be enough metal in the casting to admit of turning off the lower portion and using it for the counter-cell. A similar pattern, but lighter, and without the flange CD, will serve for the "end." A good lathe is, of course, requisite for dealing with the job, and the better the lathe the easier it will be to turn out a satisfactory article. But an ordinary plain lathe with 3-in. to 4-in. centres can be made to serve if the worker is ingenious; and if he can use "chasers" nothing else is required. The writer's tool is a plain 4-in. lathe provided with the usual chucks and face-plate, but with an extra in the shape of a fine 5-in. 3-jaw scroll chuck, which is most extremely useful. To adapt this machine for screw-cutting the following additions were made to it:—Firstly, on the driving-shaft a 2-step pulley of hard wood having one step double the diameter of the other, one 3-in., the other 6-in. diameter, to bottom of groove is fitted. This slides freely along the shaft, and can be clamped to it at any point by a set-screw. Secondly, behind, and rigidly attached to, the hand-wheel which operates the back-centre screw is another wooden pulley $2\frac{1}{2}$ in. diameter to the bottom of groove. A couple of thin gut driving belts, crossed where they pass between the bars of the lathe-bed, connect

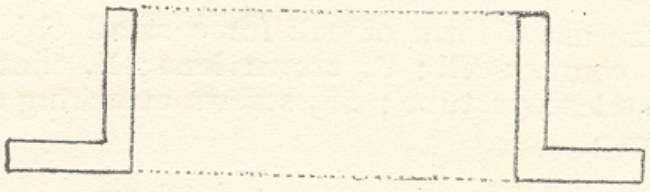


FIG. 22.—Form of casting for adjustable cell. Two castings from the same pattern will serve one for cell, the other for "end."

the shaft-pulley with that on the hand-wheel when required, and can be attached or detached in a moment. In this way the hand-wheel can be driven at the rate of 6 turns to 5 of shaft, or 12 turns to 5. Now the lowest gear of mandrel to shaft is 4 to 1; so the speed of the hand-wheel to mandrel is 6 turns to 20, or 12 to 20—*i.e.*, $3\frac{1}{3}$ to 1, or $1\frac{2}{3}$ to 1. But the pitch of hand-wheel screw is 9 threads per inch, so the mandrel makes 30 turns, or 15, per inch traverse of the poppet, according to

Comma

which step is engaged. The next speed on mandrel pulley is $5\frac{1}{5}$ to 1, which gives for 15 and 30, 20 and 40 respectively, so that we have 15, 20, 30 and 40 threads per inch which can be cut. These are sufficient for most things in telescope work. When a screw is to be cut the back centre is removed and into its socket is placed a fitting which projects forward across the T rest and engages the chaser when held in position for cutting, driving it at the above speeds. The lathe is run alternately backwards and forwards a few times till the chaser has cut deep enough to guide itself. The belt of the screw-cutting gear is then cast off and the screw finished by hand. The expert Birmingham brass-fitter will no doubt laugh at this contraption; but it works beautifully, and there are no drunk threads after it. Our first care after removing the rough exterior of the casting (an operation for which it is well to have a set of rough tools made of old files) will be to turn up the interior truly cylindrical

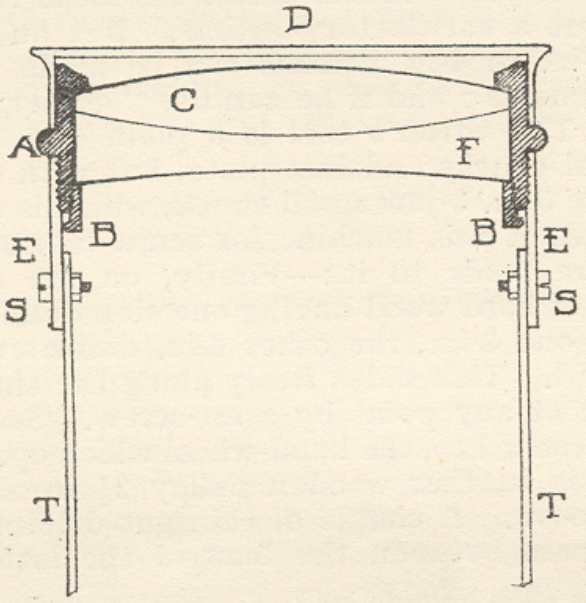


FIG. 23.—The usual form of cell for a small object-glass. A, cell; BB, counter-cell; C, crown lens; F, flint ditto; EE, end; TT, telescope tube; SS, screws attaching end thereto; D, cover-cap.

and a nice easy fit for the object-glass. A slide-rest is the proper thing for this sort of job, but it can be done with care by means of hand tools, making plentiful use of the callipers. The flange against which the crown lens beds should be left wider than will be required, to be turned down afterwards. The outside is turned down next, leaving a flange at the point to which the cover-cap will reach when fitted. Next the counter-cell may be turned up, leaving it just too large to enter. As this is a thin piece, it will be necessary to make a wooden chuck to hold it, and prevent distortion. A thick wooden ring, over which the brass ring fits loosely, will do. Split it at one side, put the brass ring on, slip the whole thing over the jaws of the scroll chuck, and expand the latter till tight. We can now turn up or screw the thin ring without fear of distorting it. A thread

of 30 per in. is suitable for the counter cell, and it should be an easy fit till very nearly home. The external thread by which the cell screws into the " end " should be a good deal coarser, 15 or 20 per inch. The " end " need not be anything but a plain cylinder, except for the internal thread at one end. The other end should be a fairly easy fit over the main telescope tube, and while in position thereon should be drilled at three equidistant points, and screws fitted, each with a nut inside the tube. The holes in the tube should be broached out to a loose fit, or

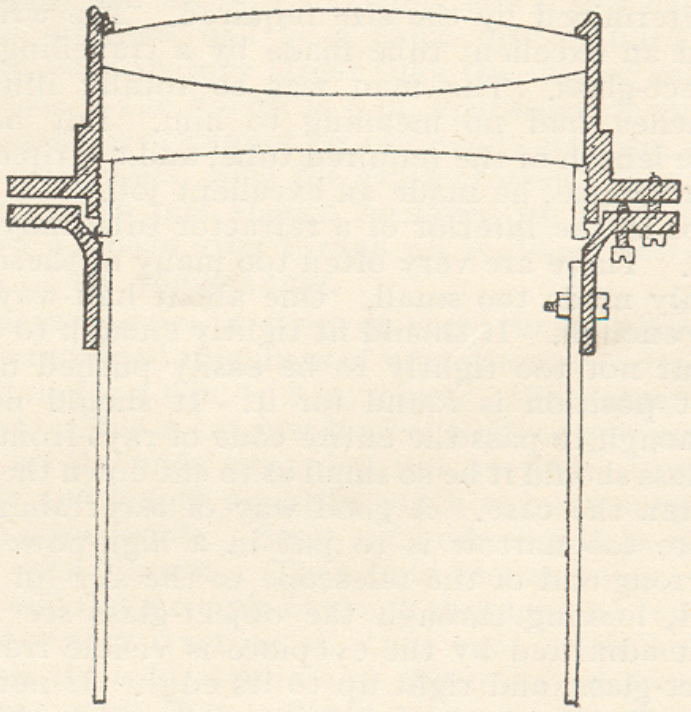


FIG. 24.—Pull-and-push screw cell. There are three equidistant pairs of screws, but one pair only is shown.

else a little longer than they are wide, to admit of a small amount of adjustment for squaring the object-glass (see Fig. 23).

This is the usual plan in small telescopes. But it will save a lot of worry afterwards if we have a cell provided with " pull-and-push " screws for squaring. A slight modification of the form of the castings for cell and end will be necessary for this (see Fig. 22.) And not only a modification, but a simplification. For the same pattern will serve for the castings for both cell and end, and if the cylindrical part be made deep enough to spare a ring turned off for the counter-cell, one pattern of the form shown will do for the lot. Fig. 24 shows in section the form of the cell when completed. Great care is necessary in making the finishing cuts on the interior of the cell. It must be truly cylindrical, an easy fit for he lenses without pressure, and with just the merest suspicion of play between brass and glass. If overdone, and too loose a fit, this may be remedied by inserting a strip of thin smooth paper as wide as the thickness of the object-glass between it and the cell. But this will not be neces-

sary to a good workman. The counter-cell must not be screwed down tight, as strain of the glass will injure its performance very seriously. A slight rattle should always be heard when the cell is shaken.

The tube, which forms the body of the telescope, should be straight, strong and rigid. If these conditions be fulfilled, its actual material is of small importance, except for appearance. Brass is, of course, the proper material for a small refractor, and up to 3-in. diameter it will not be prohibitive in cost. But excellent tubes may be made of sheet iron, tinplate, wood, or even pasteboard. The suitability of the material will, of course, be partly determined by the size required. The writer on one occasion had an excellent tube made by a travelling tinker for a 3-in. object-glass. The man was so totally illiterate that feet and inches had no meaning to him. But being given a stick of the length of the required tube, and a strip of tin equal to its circumference, he made an excellent job.

The stops in the interior of a refractor tube may be turned out of wood. There are very often too many of these, and they are commonly made too small. One about half-way down the tube will be enough. It should fit tightly enough to stay where it is put, but not too tightly to be easily pushed up or down till the best position is found for it. It should not be only just large enough to pass the entire cone of rays from theobject-glass ; still less should it be so small as to cut down the aperture, as is too often the case. A good way of ascertaining whether the stops are too narrow is to put in a high-power eyepiece, point the wrong end of the telescope to the sky (or any bright object), and, looking through the object-glass see if the tiny spot of light admitted by the eyepiece is visible from all parts of the object-glass, and right up to its edge. If not, the stops are cutting off some part of the aperture, and should be removed, or shifted nearer the eye end.

To come to the eye end, the principal working part here is the rack-and-pinion focussing movement. This is a job which is hardly one for an amateur, and we would recommend purchasing it, as also the eyepieces, and for the same reason. They can be bought at a moderate price far better than the amateur brass-fitter could make them. At least, three eyepieces should be obtained. If this number be decided on they should, for a refractor, be of about 2 in., $\frac{3}{4}$ in., and $\frac{1}{4}$ in., equivalent focus respectively. If the telescope is of 4-in. aperture or more, 4 to 6 eyepieces will be found useful, and should range from $2\frac{1}{2}$ in. to 1-5 in. equivalent focus to enable the objective to do itself justice on all classes of objects.

CHAPTER XIV.

A cell for a mirror is a totally different article from that required by an object-glass. If we are to be particular, and want our mirror really finely mounted, it will be an engineering job, calling for a heavy iron casting and a powerful lathe to machine

it—a job for a machine-shop. But the Newtonian is a very tolerant instrument, and will perform well in a mount which the most unpretentious object-glass would disdain to be seen in. Draper and With used to sling their mirrors in a simple leather strap, with a stout board for a backing, at the bottom of a square wooden tube. And though it is desirable to have something less rough and ready than this, we can provide a very excellent cell which will hold the mirror quite securely in adjustment and also protect it from moisture and tarnish when not in use with no more elaborate tool than the plain lathe aforesaid, a set of stocks and dies for screwing, and a few hand tools. The first item required will be a thick disc of hard wood (oak is excellent), very slightly larger than the mirror and at least 1 in. thick; more if the mirror is 8 in. aperture or over. If a sufficiently thick piece cannot be obtained, get two, and screw and glue them together, with the grain crossed. The side on which the mirror is to rest should be faced up truly flat, or, better still, have a raised ring turned on it about three-quarters the diameter of the whole thing.

We next require a strip of sheet brass about 1 in. wider than the combined thickness of mirror and wooden disc; 1-16 in. sheet will do for a 6 in. to 8 in. mirror. For larger sizes it should be thicker. This is cut just long enough to go round the wooden disc and let the ends meet, but not overlap. Cut a strip about 1 in. wide and length equal to width of large strip, and sweat it on to the joined ends. Strip and ends should be tinned and well smeared with Fluxite. Then hold in hand-vice, ends meeting, and drill and put a couple of rivets through and tap up. Reverse vice, and repeat riveting at other end. Now hold in flame of blow-lamp till solder runs and shows round rivet ends. Now you have a joint that will not give way for a trifle. Slip the collar so formed over the wooden disc, drill half a dozen holes round into the wood, and insert screws, and there is your cell. It requires nothing more but means of attaching to telescope tube, something to keep mirror from falling out, and a cover-cap.

To keep the mirror in, we need not go to the trouble of fitting a rim. Three small blocks, cut out of $\frac{1}{4}$-in. sheet brass, will do. They should be spaced at intervals of 120 deg. round the inside of the cell, and either soldered to it, or, better, attached by drilling and tapping and putting a small counter sunk screw through from outside. When thus attached, the mirror can be removed and replaced by merely unscrewing the blocks. If they are soldered, the screws holding the brass to the wood backing must be removed and the whole metal ring lifted off. As these are wood screws, frequent removal is apt to make them loose in their holes. The method of attaching the blocks with screws is therefore to be preferred.

A simple method of attaching the cell to the tube is shown in Fig. 25. AB, CB, DB are pieces of flat iron or brass bar attached to the wooden back of the cell by screws as shown, and making angles of 120 deg. with each other. Each is long enough to extend considerably beyond the circumference of the cell, and the outer ends carry holes, the centres of which are

at the angles of an equilateral triangle. These three holes fit over three screwed brass or iron rods, rigidly attached to the telescope tube. Each rod carries two nuts. One nut is placed on each rod and screwed up about $\frac{3}{4}$ in. Then the cell is slipped over the rods, the screwed ends entering the holes until stopped by the nuts. The second nut is then screwed on to each rod, and screwed home. Obviously, any desired adjustment can be obtained by slacking off one nut and tightening the other where required. The cover-cap merely requires a piece of sheet metal cut to a circle a little larger than the cell, and a strip of length equal to the circumference of the latter. The ends of this are joined, as described for the body of the cell, and it is soldered to the circular piece. It should be an easy fit for the cell, and to secure that it is a circle it should be slipped partly on to the cell, the latter inverted on to the piece of sheet,

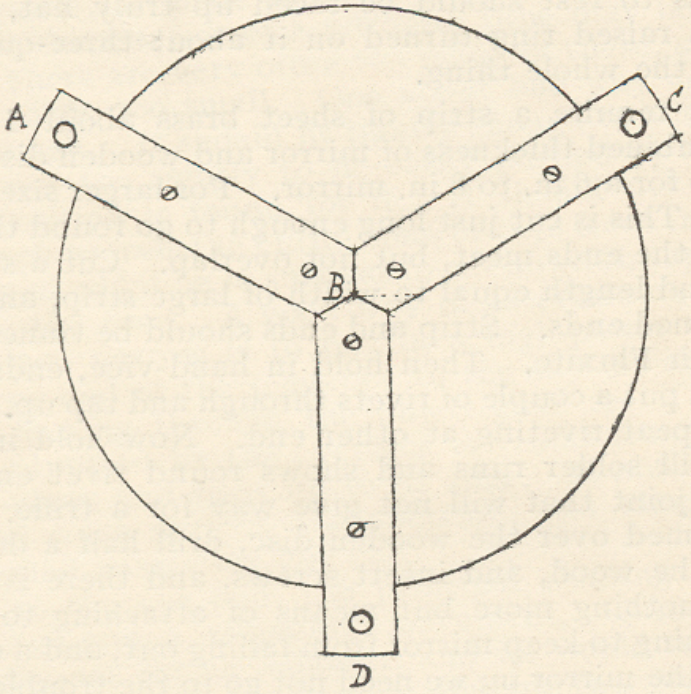


FIG. 25.

and the strip soldered while in this position, taking care not to solder it to the cell itself. A piece of the same strip, bent to a suitable shape and soldered to the middle of the cover outside makes a handle for lifting off. The whole thing is much like the lid of a saucepan. For a large cell, anything over 8 in., it is desirable to have the cover-cap convex. It can easily be made so by laying the circular sheet of metal on an anvil (failing one, the lathe bed will do) and tapping lightly all over with a hammer with a convex face. Begin in the centre and go round in increasing circles to the circumference, repeating the operation till the desired degree of convexity is attained. Any spot which remains too flat should get a few extra taps of the hammer If the sheet is brass this operation may make it brittle, and to prevent cracking it should be heated dull red, and then plunged in cold water, when it will be as soft as before hammering.

Reflector Tubes.

As the cell for a mirror is quite a different thing from one for an object-glass, so a tube for a reflector may be a much rougher affair than a refractor tube, and yet give satisfaction. Indeed, many good reflectors have no tube at all, but only a skeleton frame-work. The writer uses, for testing mirrors, a queer-looking affair which does not in the least resemble a telescope, but is tube and tripod in one. All of the "tube" except one side is absent. The mirror rests on a sort of bracket bolted to one end of this side (a mere plank, stiffened by a rib on the under side). The flat mount and eye-tube slide up or down the same, and are clamped at any position by a set-screw, while the whole is supported by a pair of pivoted legs attached to the end remote from the mirror support, these being pointed at the lower ends and telescoped like the legs of an old-fashioned camera stand. This rough and ready affair will take mirrors of any focal length up to about 8 ft., and they often perform better on it than in an elaborate tube. However, we do not propose to recommend this as a permanent style of mounting. There are two alternatives in material: sheet metal or wood. And there are three or more in shape: round, square, or hexagonal. A square wooden tube is simple, and easily made, and mirrors perform excellently well in such a one. An octagonal or hexagonal wooden tube will make a very neat mount, but it is a job for a skilled joiner. A cylindrical tube of sheet metal looks the best of all; but, alas! its looks are about its only recommendation, unless it is to be housed under the dome of an observatory. In the open air a sheet metal tube will make a mirror play the most extraordinary tricks, on clear, calm nights, owing to its sensitiveness to changes of atmospheric temperature. The upper side of the tube radiates its heat to the clear sky and becomes much colder than the lower. The result is that the upper half of the mirror cools faster than the lower, and the images take the queerest shapes. The writer has wasted hours in times gone by tinkering with adjustments, n the vain endeavour to persuade the images of his first reflector to come straight, and only tumbled to the real cause when he observed that the images always came straight when the telescope was left a few minutes pointing to the zenith, that the distortion was always on the side of the image corresponding to the side of the tube which happened to be uppermost, and that on windy nights there was no distortion at all, nor when the sky was partly clouded. Later on I devised a tube which combines in itself the convenient shape of a metal one, and the non-conducting properties of a wooden one, and which the veriest novice in the workshop will have no difficulty in constructing. This I have named the "Built-up Tube," and I now proceed to describe it, though, indeed, the accompanying photograph, Fig. 26, is self-explanatory. It shows a built-up tube carrying a 10-in. mirror, made by me several years ago, and mounted on a very handy form of equatorial, both tube and equatorial being the work of the owner, a well-known electrical engineer.

The material of the tube is nothing but plain wooden laths, attached to six metal rings, which rings may be either outside or inside the tube, according to fancy or convenience. One ring goes at each end, two in the middle where the tube is held in its cradle. One is under the screws of the flat mount to stiffen the tube against the pull of the springs, and the sixth is about 6 in. above the mirror end, for extra strength to support the weight of mirror and cell. The rods on which the mirror cell slips, and the nuts of which serve the double purpose of support and adjustment, may be very conveniently attached to both these two lower rings, and the whole arrangement of rings and rods can be made to take off on removing a few screws.

The rings are very easily made, by bending brass strip and lapping and soldering the ends, as in the case of the cell. The laths may be either fitted skeleton-wise, as in the photo, or close together.

When the tube is made it can be either left uncovered or covered with any material that necessity or fancy dictates. If intended for use in a covered observatory, no covering at all is needed, or a very light covering, such as glazed calico, canvas, or even brown paper, will serve. For out of doors we must have something weatherproof. Light sheet zinc, with the edges of the sheets overlapping and soldered, is excellent. If a cap of the same material is made to fit over the open end, and the telescope when not in use is placed mirror end downwards and secured against wind, the interior of the tube wil be so dry that the silver films will last as well as if indoors. A $10\frac{3}{4}$-in. telescope of this kind stood in an exposed position with me for three years, and after that the film was as fresh as the day it was deposited, and when the instrument was sold to a planter in Ceylon it went out, *in statu quo*, without its being necessary to re-silver it.

Another excellent covering material is *ruberoid* (made for roofing). It is much cheaper and lighter than zinc, and is equally weatherproof, while it has the additional advantage of being a non-conductor of heat. If damaged it can be repaired in the same way as a bicycle tube. As a roofing material for an observatory it is unrivalled. A 12-in. reflector, with a built-up tube covered with this material, ~~is waiting in my workshops to go out to India when the war is over.~~ was sent out to India in 1918. The whole tube, mirror and all, is not more than one man ~~can~~ could lift.

If the tube is to be clothed with an exterior covering of some sort, it will be necessary to have the rings inside; but, if not, and the instrument is to be under a weatherproof shelter, a very good appearance may be given it by using laths of some of the finer woods, putting on brass rings outside, staining and varnishing the laths and keeping the rings polished. Two, or four, brass handles attached to the tube will be found a great convenience for lifting it or for rotating the tube if it is mounted equatorially and means provided for rotating in order to bring the eye-tube to a convenient position in whatever direction the tube is pointing. The comfort and convenience of this arrangement can hardly be overrated.

several others have gone to other parts of the globe.

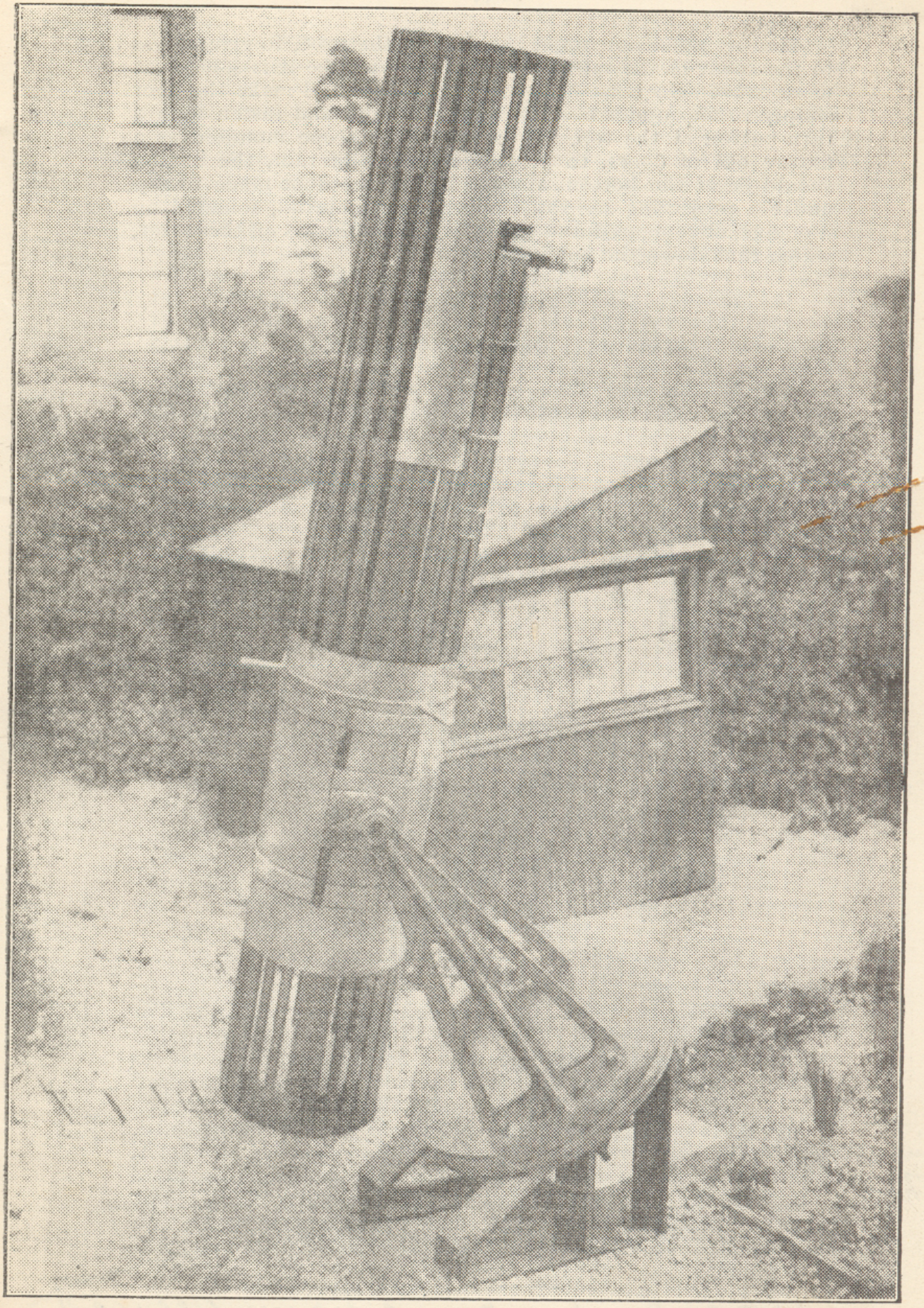


FIG. 26.

And we must not forget the door in the tube, to give access to the cover of the mirror. In a built-up tube it is somewhat more convenient if we dispense with hinges and make the door simply to slip under a catch at the bottom and fasten with a turn-button at the top. In case of a telescope mounted as a fixture out of doors, to prevent entrance of rain, the button should be at the bottom and the top of the door made to slip under a projecting strip of the covering material, soldered on if of zinc, or cemented if of ruberoid. This throws off the water, which runs down the outside.

CHAPTER XV.

The Flat Cell and Suspension.

The flat mount I now describe differs in some particulars from that made by Browning, and later by Calver. The first

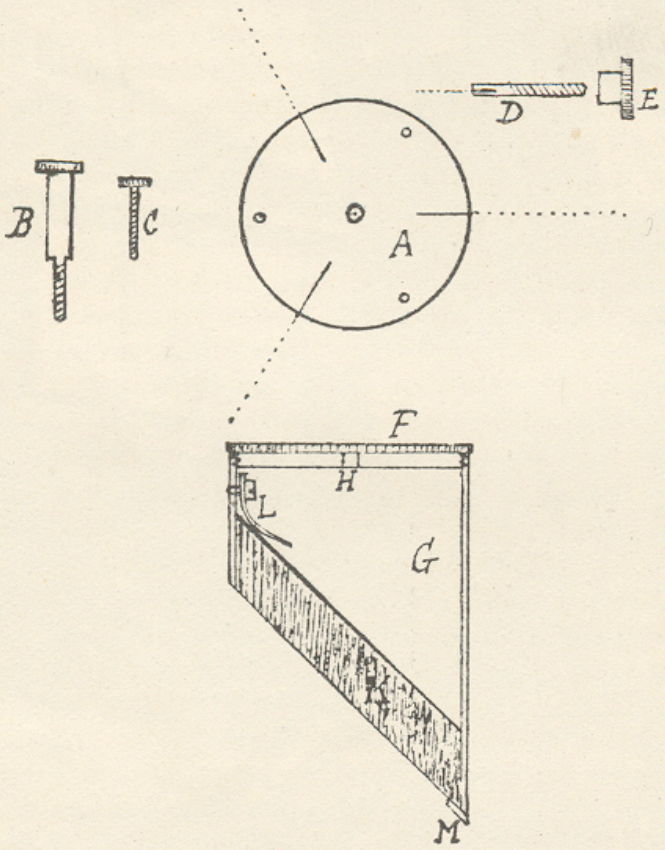


FIG. 27.—Details of Flat Cell and Suspesnsion.—A, brass disc suspended in tube by clock-spring supports (shown by dotted lines). B, large shouldered milled-head screw which passes freely through central hole (not screwed) in disc A till stopped by shoulder. C, one of three small milled-head screws tapped into holes passing through to outside of main telescope tube. D, milled nut for same. F, another disc, equal in size to A, converted into a milled-edge screw-cap screwing into brass tube G. H, hole in F tapped to take the screw B. K, glass plane. L, light brass spring and screw holding same. M, small piece of brass soldered to tube G as stop to hold glass in place.

a line dropped out here

into 3 holes shewn round circumference of disc A; D one of 3 screwed rods, attached to clock-springs, and fitting into holes passing through

thing required is a pair of brass discs, equal in diameter and thickness, and just a little larger than the minor axis of the flat. These can be cut out of a piece of quarter-inch brass sheet. Select a piece of suitable size, clamp it to the face-plate, and cut out the disc with a parting-tool. Just before cutting quite through, turn up to the size required and face outer side flat. The central hole may also be drilled at the same time. Having done as much as possible on the face-plate, we finish parting out the disc and proceed to cut out another in the same way. Our pair of discs being cut out we finish one of them as follows. The edge is turned up plain and square, and three radial slots are cut in it at intervals of 120 deg., reaching half-way to the centre, with the hacksaw. Midway between these slots three $\frac{1}{8}$-in. holes are drilled through the disc near its circumference, tapped, and milled-head screws fitted. In the centre, if this has not been already done on the face-plate, a $\frac{1}{4}$-in. hole is drilled, but *not tapped*. A milled-head screw of the form shown at B, Fig. 27, is made from a piece of $\frac{1}{2}$-in. brass rod. The end is turned down to pass *loosely* through the hole in the disc, and a screw-thread cut thereon, not quite up to the shoulder. We now turn our attention to the second disc. As its edge will have to receive more elaborate atttention than that of the first, we must find means of chucking it so as to leave the edge free. We may do this by taking advantage of the central hole. This is to be tapped out to fit the screw B, so we may as well do it now, and turn up and screw a short piece of brass rod to fit it and serve as a hold for the three-jaw chuck to grip. But a more secure way is to solder a short piece of rod to it temporarily. If a short piece of the end of the rod is turned down to fit loosely in the hole it will secure the centring. But if we choose this method of holding, it will be better to defer the tapping of the hole till afterwards. Having, by one means or the other, securely chucked the disc, before proceeding further with it choose a piece of brass tube of the *same gauge* as that which formed the cutter which cut out the flat that is to be mounted. Cut it to a length of one and a half diameter, or a little more. For this, of course, the flat will be a neat loose fit, and its external diameter will be about the same as that of our two discs. Turn up both ends of it true and smooth.

Now we turn back to the disc in our scroll-chuck. Turn down the edge till it will just not enter the end of the prepared piece of tube, but leaving a narrow flange of the original diameter. Cut a thread of 30 or 40 per inch on the reduced part *right up* to the flange. This is more easily said than done, especially by an amateur. It will be easier if a narrow groove is turned right up against the flange, and just a little deeper than the bottom of the thread that is to be cut. The foremost tooth of the chaser will run into this instead of jamming up against the flange and forcing the other teeth over the thread. It might be supposed that $\frac{1}{4}$-in. thickness would not give much room for flange, groove, and thread, but there is enough. Having cut the thread satisfactorily we next cut an internal thread of the same pitch in one end of the brass tube aforesaid, and see

that the disc screws smoothly home up to the flange. Before removing the holding-piece from the disc do not forget to knurl the flange.

The next step is to cut the end of the brass tube to an angle of 45 deg. This is a job for a steady hand and a fine hacksaw. First rotate the tube in the lathe, with the screwed end gripped in the scroll-chuck, and mark a line round it at a distance from the plain end equal to the external diameter of the tube. Now take the hacksaw, and, starting from this line, cut back to the end, aiming to come out just at the edge. If you cannot make a good shot, aim to come out too far down rather than not far enough, as then a file can take off the excess. Use a big flat file to take out the saw marks. It is not a bad plan to finish up with a rub on a large, smooth flag-stone with some water. Having got the diagonal cut finished true and clean, there is nothing left but to solder a tiny point cut from thin sheet brass at M, Fig. 27, and make a very light, flat spring and secure it with a screw at L. The spring should be adjusted only *just to touch* the back of the flat when in place. To put the flat into its cell, unscrew the cap F and the spring L, push flat in from back till its lower end engages the stop M. Replace L and screw in cap again.

We now turn to disc A. This is to be suspended in the axis of the telescope tube by three pieces of steel spring, which, being edgewise to the mirror, stop the minimum possible amount of light. The spring of a discarded American alarm clock will supply excellent material. Cut three equal lengths of such dimensions that when pushed into the radial slots in the disc and the latter placed in the centre of tube the outer ends of the pieces of spring will be a little short of touching the interior of tube. Te secure these firmly in the slots they are sweated in with solder. If the pieces of spring are cut by snapping them off with a pair of pliers, there will be just enough burr on the ends to grip the solder and make sure that they will not fetch away with any end-pull. To the outer ends short pieces of screwed brass rod are attached in the same way, slotting with a hacksaw and sweating in with solder. Each screwed end is provided with a milled nut.

To assemble, pass the three screwed ends through the holes provided in the main tube and screw on the nuts. Adjust the nuts, tightening or slacking off as required till the hole in disc A is truly in the centre of the telescope tube. Screw the three small milled-head screws, C, into place till their points project about $\frac{1}{8}$-in. below the disc. Push the screw B through the hole in disc A, and with the other hand bring the flat cell below the disc and screw B into the hole H. Screw up till the points of the screws C bear against the disc F. Before tightening right up, rotate flat cell till on looking through eye-tube the reflection of the large mirror is as nearly central as possible. Bring it completely central by means of the adjusting screws C. Only one part more of the flat cell remains now to be made—viz., the cover to protect the flat when not in use. This is easily made of very light sheet metal. Brass looks best, but zinc

or even tin-plate will do. Cut a piece of suitable size, roll it on a piece of brass tube of same gauge as the flat cell, and solder the seam by running the soldering bit along it, with just the minimum possible amount of solder to make a joint. If afraid of solder taking hold of the tube underneath, put a strip of paper under the joint. Now solder a circular piece of same sheet on the end. When cool it will pull easily off the shaping tube and will be a nice easy fit. On no account let it be tight, or it will disturb adjustments. Opticians' cover-caps for flats are nearly always too heavy and too tight. The very lightest sheet metal obtainable is best, and the lighter the less likely it is to be too tight. Put a bunch of cotton-wool in it. If chloride of zinc was used in the soldering, give the whole thing a good wash in hot water and dry well before using. If zinc be used for the caps, fluxite will make the soldering very easy ; but for brass, chloride of zinc works more easily. Anyone who has occasion to do a variety of soldering jobs will find it handy to keep a supply of both. But the chloride flux must be thoroughly washed off when the job is done, or corrosion will set in very soon, especially with iron. And it is hardly necessary to remark that chloride of zinc is a very undesirable neighbour to silvered surfaces.

CHAPTER XVI.

STANDS.

Having satisfactorily completed the optical parts and the tube with their accessories, the telescope maker is confronted with his last and not least formidable problem in the stand for his in strument. It must provide two things—rigidity and freedom of movement in all directions. It must be capable of catching its object, whatever be its altitude and azimuth, and of holding it in the field of view without vibration. It may be said at once that this last condition is, strictly speaking, unattainable unless the instrument is housed in a building which excludes wind. No telescope stand, however massive and well made, will hold the instrument vibrationless in the open on a windy night. Therefore, although much useful work may be done by telescopes mounted in the open air, the open-air astronomer must expect to lose many good observing nights from the effects of wind ; and good nights are too few to waste any of them if it can be avoided. Nights of strong wind often give bad seeing, but sometimes they give the very best, and they nearly always have a very transparent atmosphere, especially after rain, so it is a pity to waste them. It is, therefore, desirable that the telescope stand should err, if at all, on the heavy side, and if the observer can spare the expense of a covered observatory he will find himself abundantly repaid in comfort and increased opportunities for using his telescope. But of the observatory we propose to treat later.

As there are many kinds and sizes of telescopes, so there are many kinds of stands to suit them. A small instrument, 3 ins. aperture or less, can be worked very well on the ordinary pillar-and-claw stand which may be seen in any optician's window, and it is so familiar that it need not be here described. If a gate-post, sun-dial, or other rigid stone support of a convenient height is available, the pillar-and-claw stand supported thereon will be more free from vibration than any other kind of support for a telescope in the open air can possibly be.

For telescopes a little larger the folding wooden tripod, or "garden stand," is very popular. But its rigidity leaves much to be desired, and if a breeze prevails it is very apt to try the temper of the observer. Such a stand is often provided with an equatorial head, and must then have screw feet for levelling as well as a pair of attached spirit-levels. It must also have sockets provided to fit the points of the levelling screws. This may be done in any of several ways. Lay a square of concrete on the garden path, back yard, or wherever Fate has given you to observe, and when it is set get the correct adjustment for your stand, mark the exact position of the screw-points with chalk, and cut sockets with a cold chisel. I have myself done the trick on a grass lawn by sinking three heavy pieces of stone in holes dug in the turf. Each stone had one flat side, which was placed uppermost and flush with the surface, and the sockets were cut in these. After a few months' growth of the grass the stones were quite immovable. This method worked well with a 4-in. refractor for many years. Or, again, one may get three square pieces of heavy steel plate, having $\frac{1}{2}$-in. holes drilled

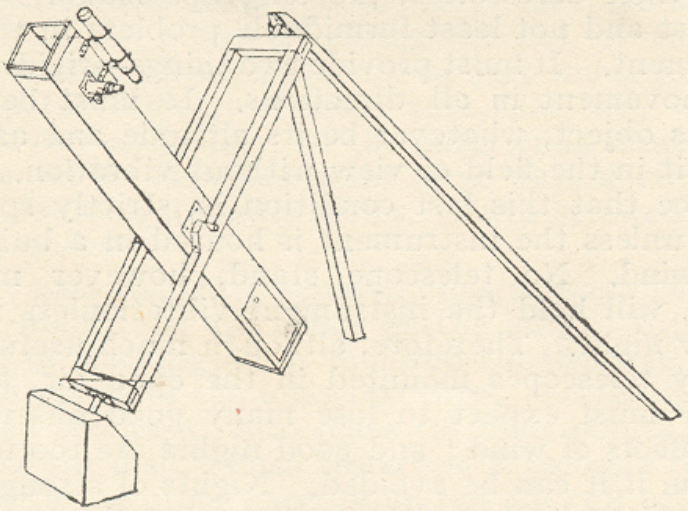


FIG. 28.

in their corners. These can be set down anywhere and fixed by driving 9-in. iron bolts through the holes, and sockets can be drilled in the plates. Plates 6 ins. square will be quite large enough.

A tripod stand of the most ordinary kind, if fitted as an altazimuth, can be transformed into a plain equatorial by simply removing the fittings from the top plate, fitting to the latter by a hinge at one side a second plate, with a wedge cut to an angle equal to the co-latitude of the observer between the two

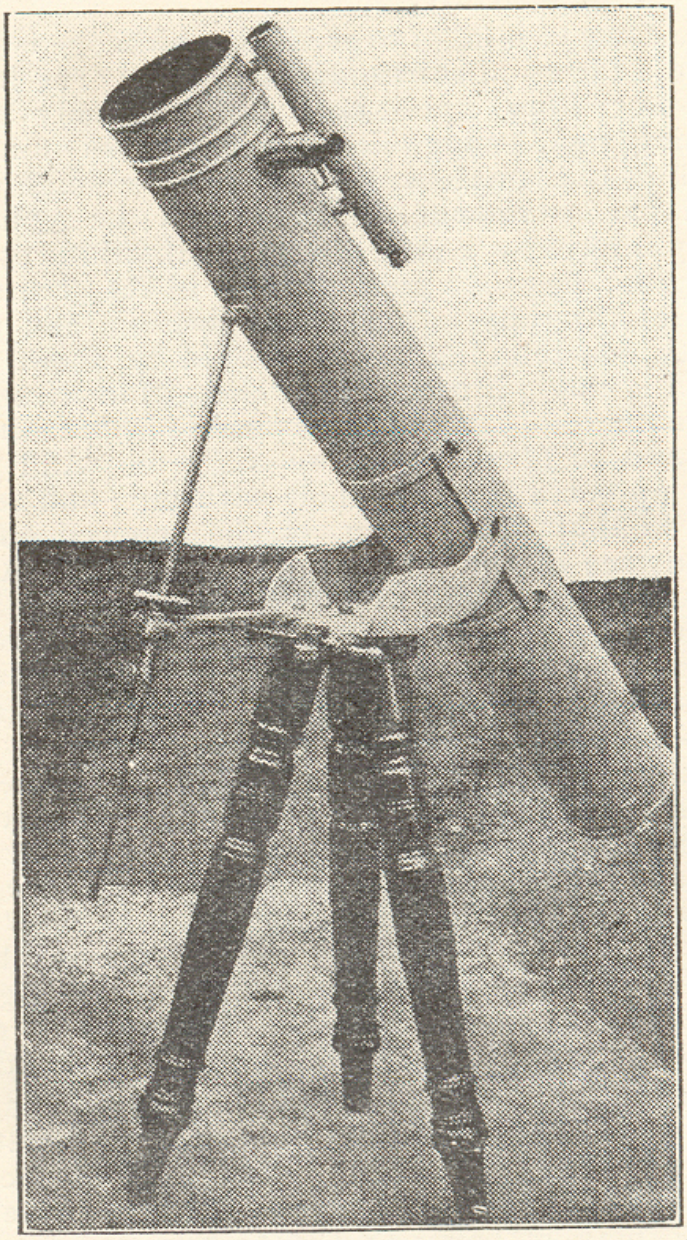


FIG. 29.

plates and then replacing the telescope cradle on the upper or hinged plate. In this way the altazimuth becomes a universal equatorial, adaptable to all latitudes by simply changing the wedge.

In the introduction to *Norton's Star Atlas*, p. 16, there is illustrated a neat method of turning a common pillar-and-claw telescope into an equatorial. A light wooden folding tripod, such as any joiner could construct, has fitted to the top a stout wooden block, cut off at an angle equal to the latitude. In the

face of the sloping top is a groove which fits the " pillar " of the telescope, and in which it is retained by two or three screw clamps. The " claw " legs are folded and quite out of the way. When it is desired to use the telescope for terrestrial views, it can be detached by unscrewing the clamps and set on its own feet. The above devices are quite successful with refractors up to about 4-in. aperture.

When we come to 6-in. or over, if the telescope is a refactor, it must have a far more substantial support. The iron column on which observatory equatorials are commonly mounted is the only thing rigid enough for a refractor of 6-in. aperture or more. But the amateur who is lucky enough to possess such a valuable instrument, if he has not the regulation iron column, may improvise a very effective substitute by procuring a 6-in. iron pipe, digging a good big hole in the ground, wherein the pipe is set carefully in a vertical position, and then filiing the hole with concrete. The hole should be about 3 ft. deep, if the ground is clay ; if rock is near the surface it need only be carried down thereto. When the concrete is set, the inside of the pipe should be filled with more concrete. And just before filling right up get a long iron bolt with nut, and set it head downwards so that about 3 in. of the screwed end projects above the surface of the final layer of concrete. A 9-in. bolt will do first-rate, but a longer one will do no harm. If the pipe is in two sections, put in, instead of the bolt, an iron rod running the whole length of the pipe. On this, either an altazimuth or equatorial head can be secured by means of the bolt. If the observer's pocket cannot rise to an observatory, it is easy to arrange matters so that the telescope can be carried indoors, leaving the stand and moving parts *in situ*, and covering them with a piece of tarpaulin, or with some kind of weatherproof cap made of sheet metal. And if at any time the means to erect an observatory are forthcoming it can be *built round* the already existing stand without disturbing anything. The concrete-filled pipe gives the maximum possible rigidity, and any kind of motion head, whether altazimuth or equatorial, can be readily attached to it by means of the embedded bolt.

For reflectors we require stands of a different pattern altogether from those suited to refractors, and of a nature much more easy for the amateur to improvise. This is due chiefly to the fact that the eye-tube of the Newtonian is near the top of the instrument instead of being at the bottom as in a refractor. Short and stout, therefore, must be our motto in the case of reflector stands, and consequently the highly important quality of rigidity is much more easily attained. In addition, it is actually easier to construct a simple form of equatorial for a reflector than even the barest kind of altazimuth. On page 71 of the *English Mechanic*, January 11, 1918, is a reproduction of a simple and most effective stand of a kind suitable for reflectors up to 12-in. aperture or even more. It was reproduced from drawings supplied by the present writer to Professor M. T. Fullan, of the Alabama Polytechnic Institute, representing a stand constructed by me which saw ten years' service, carrying

first an $8\frac{1}{2}$-in. and afterwards a $10\frac{3}{4}$-in. reflector, and was only dismantled to make way for an 18-in. Calver equatorial with fully equipped dome. Fig. 28 shows the same kind of stand reduced to the simplest possible form. It possesses the important advantage that it can be constructed in the simplest manner without slow motions or circles, and all these can be added afterwards as required. The whole is constructed of 3-in. square timbers, except the concrete block which supports the lower end of the polar axis, two short iron posts, to which the sides of the triangle are bolted, and the pieces of metal rod forming the trunnions.

Fig. 29 shows a portable form of altazimuth stand for a smaller reflector. It represents a tube and stand constructed for one of the writer's $6\frac{1}{4}$-in. mirrors by a workman in the G.S.W. Railway Works at Inchicore, Dublin, and is self-explanatory.

It often happens that the task of the amateur telescope-builder is facilitated by the possession of some article, perhaps long consigned to the lumber-room, which admits or even invites being utilised for a stand.

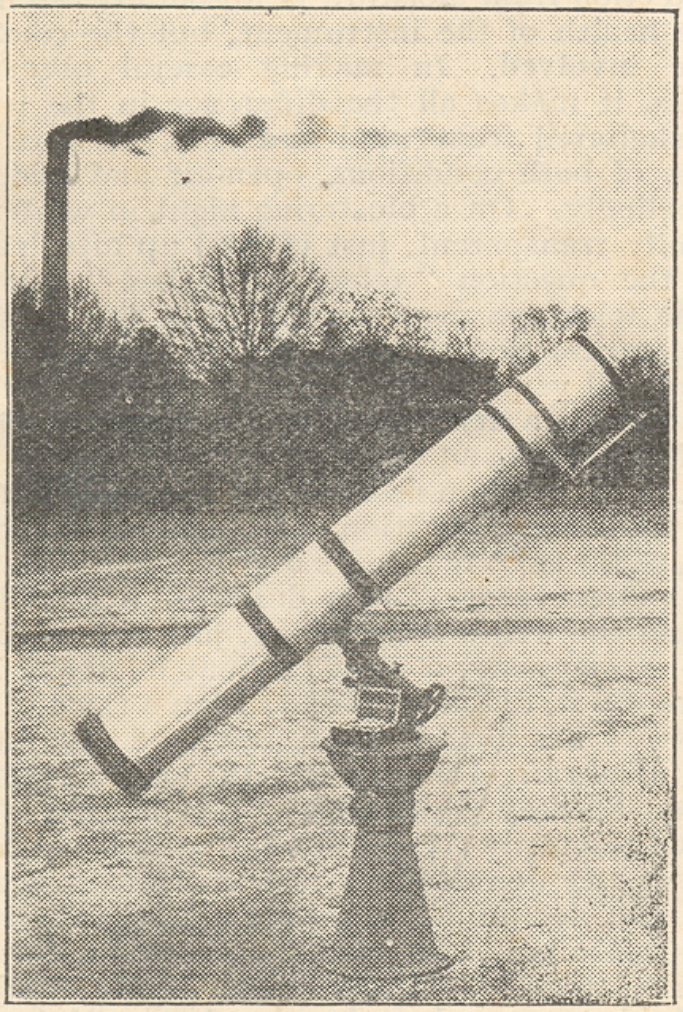


FIG. 30.

Fig. 30 is an example of such adaptation in a very neat reflector mounted on a cast-iron stand which certainly meets

all requirements for rigidity, but was obviously designed for something else. Such a stand would accommodate quite well the best equatorial head the art of the optician can produce, and would not disgrace the most admirably appointed observatory. The photo also shows the door in the main tube for removing cover of mirror, handles for rotating tube, balance weight, and other details.

CHAPTER XVII.

The Observatory.

The possessor of a telescope of such a size and weight that it must be a fixture—that is to say roughly any instrument much over six inches aperture of either class—must consider means of protecting it from the weather. Especially is this the case if the instrument is a good equatorial, with the usual circles and movements. If a driving-clock forms part of the outfit, efficient protection from moisture is absolutely essential. And not only the health of the instrument, but the comfort of the observer are involved. In making careful observations or measurements, it makes all the difference in the world if the observer is sheltered from wind and cold. I have had years of experience of both conditions, open-air and under a dome, and speak feelingly. On a blustering night in winter, with the sky delightfully transparent, just cleared up after rain, or perhaps snow, the question "telescope or bed" often presents itself. If the telescope means standing in wet grass or snow, with a temperature near freezing point, and a keen edge on the wind, bed will very often have the decision. But it will be otherwise if there is a dry floor, a roof to keep out the worst of the wind, and a chair to sit on.

The Rev. E. L. Berthon deserves the gratitude of all amateur astronomers for his simplification of the construction of a private observatory, so far as to reduce its cost to about £25. But even the "Romsey Observatory," as he described it, is still needlessly expensive, and the writer constructed, just before the war sent prices up so disastrously, a most efficient telescope house with a revolving roof 8 ft. diameter for less than a third of that price. This observatory has already been described and illustrated in the *English Mechanic*, January 29, 1915, under the name of the "Modified Romsey Observatory." It housed a 5-in. equatorial most satisfactorily; and a similar building, and even more satisfactory, nearly double the size was afterwards constructed at a cost of £30, for an 18-in. Calver equatorial with driving-clock. Both these buildings were constructed with two leading principles in view:—(*a*) Plenty of air space, and thorough ventilation both over and *under* the floor; (*b*) hemispherical domes. (*a*) Secures absolute dryness, summer and winter; (*b*) free movement of the telescope in all directions, with the minimum of space, and, not less important, greatly reduced wind resistance.

The great reduction in cost was secured firstly by the designer being his own workman; secondly, by the use of galvanised iron instead of match-boarding, and "ruberoid" instead of canvas. Indeed, a very efficient cheap weatherproof, light and comfortable building could be erected, by dispensing with galvanised iron, and using ruberoid and timber framework only for the whole thing. The frame should be made stiffer to compensate for the loss of the rigidity of the galvanised iron. Indeed, not a telescope house only, but a very comfortable cottage could be built of timber and ruberoid, and anyone contemplating the erection of an observatory would be well advised to write to the makers, The Ruberoid Company, 81 Knightrider Street, E.C., for their descriptive booklet. The material is

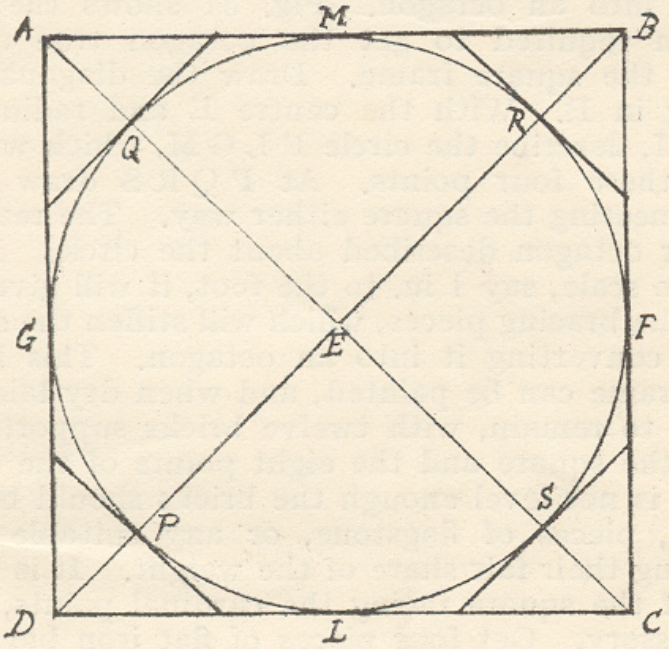
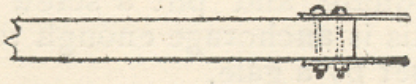


Fig. 31.



less than half the price of canvas, does not require to be painted, is absolutely weatherproof, light, non-conducting, and practically everlasting. It is also very easily repaired if accidentally damaged. The repair is effected in much the same way as that of a punctured bicycle tyre. A cement is supplied by the makers for joining the edges of the sheets. A little of this is painted over the damaged spot, left for a few hours till "tacky," and a piece of ruberoid pressed on to it. In twenty-four hours it will be solidly united to the sheet, and the puncture permanently sealed. The usual colour of ruberoid is black or grey, but green and red shades can be supplied if desired. It is also made in three thicknesses—1, 2, and 3 ply; but 1-ply is amply strong enough for observatory work. The best foundation for it is solid and continuous boarding, but it succeeds quite well if stretched over a skeleton frame, provided the intervals are not greater than about 6 in. to 8 in. If wider than this,

wire netting may be nailed on as a support for the ruberoid. The 3-ply is stout enough to support itself with much wider gaps between the timbers. A small telescope house may be constructed as follows. I describe my own 8-ft. dome, with modifications suggested by experience.

For a dome this size we require no foundation—properly so-called—at all. The building does not even rest directly on the ground, but on a few bricks, which may be simply laid down on any level spot. There is, therefore, a clear air space as deep as the thickness of a brick right through underneath, a most important point for the dryness of the interior.

The first thing to make is a square frame of 3-in. timbers, 8 ft. side, and to brace the angles of this by cross-pieces, turning the square into an octagon. Fig. 31 shows the geometrical construction required to get the octagon true and regular. A B C D is the square frame. Draw the diagonals A C, B D intersecting in E. With the centre E and radius E F, E G, E I, or E M, describe the circle F I, G M, which will touch the square in these four points. At P Q R S draw tangents to the circle, meeting the square either way. The resulting figure is a regular octagon described about the circle. If the figure be drawn to scale, say 1 in. to the foot, it will give the correct lengths of the bracing pieces, which will stiffen the square frame as well as converting it into an octagon. This having been done, the frame can be painted, and when dry laid in position where it is to remain, with twelve bricks supporting the four corners of the square and the eight points of the octagon. If the ground is not level enough the bricks should be packed up with slates, pieces of flagstone, or any suitable material till all are taking their fair share of the weight. It is best to have the sides of the square facing the cardinal points, though this is not necessary. Get four pieces of flat iron bar, about 3 ft. long (or more if the soil is soft). Point them at one end and drill a $\frac{3}{8}$ in. hole in the other, and drive one into the ground at each corner of the square, and put a screw through the hole into the timber. This is anchorage enough to secure the building against being upset by a gale.

Now we want eight pieces of the same 3-in. scantling, 4 ft. long each, and cut off nice and square at the ends. We also require sixteen pieces of stout hoop-iron: $\frac{1}{8}$-in. thick by $1\frac{1}{4}$ wide will do nicely. The pieces should be 6 ins. long and each have four $\frac{1}{4}$-in. holes drilled in it. It will be well to clamp all the sixteen pieces together into a block and drill them as one solid piece, thus securing that the holes are equidistant and the pieces interchangeable. We attach two pieces as shown in Fig. 31 to each of the 4 ft. posts by putting a pair of $\frac{1}{4}$-in. bolts through Then the posts are set upright, one at each angle of the octagon, the projecting irons embracing the frame, and secured to it by putting two more $\frac{1}{4}$-in. bolts through the remaining two holes in the iron. The holes in the timber are bored, while the irons are held *in situ*, with a $\frac{1}{4}$-in. bit, and, to make sure of coincidence on the other side, should be bored about two-thirds through, and then the bit restarted at the opposite side till the holes

meet. Put bolts in and screw up tight. I freely admit that this is not joinery ; but just here we do not want joinery. To mortise and tenon the timbers would weaken them and leave entrance for water to rot them, and besides we want our observatory to be dismountable, so that in case of removal it can be taken to pieces and re-erected with a minimum of trouble. This the bolts and nuts provide for.

When the eight posts are secured at bottom, we must next see that they are vertical, and fix them so by nailing a batten from each to the next. These should be about 1 in. by 2 ins., and their upper edges should be flush with the tops of the posts. Later on they will be used to screw the upper edges of the galvanised iron sheets to. We now come to an important piece of work, the making of the circular wall-plate. We require a quantity of 1-in. planks, the wider the better, and from these arc pieces are to be cut, 4 ins. wide, and having the outer curve 4 ft. radius. The number of these required will depend on the width of the planking. Do not throw away the convex pieces cut out in making these segments, for we shall need them later on. We will require sufficient arc pieces to make *two* circles 8 ft. in diameter to the outside edge, and these are to be placed one upon the other, with the segments " breaking joint," and screwed together, eight 2-in. screws being used in each segment. This makes a stiff wooden ring, which we now place in position on the eight posts, and secure it by driving a long screw through to into the top of each post. 5-in. screws should be used. After this is securely in position, we may proceed to fix the galvanised iron sheets, if this is the covering material chosen. 4 ft. and 5 ft. are standard lengths for the sheets. For our little house, 4 ft. will be convenient, but as this will only reach just to the upper edge of the foundation frame it will be well to tack a strip of ruberoid or sheet-zinc below this, 5 in. wide, to conduct water, which runs off the iron, clear of the timber. At the angles of the octagon where the corners of the square project, bent pieces should be inserted of an L shape, to form gutters to conduct water from the upper surface of the frame. If the galvanised sheets are neatly fixed at the overlaps, and attached to the timbers by three screws at top, and as many at the bottom and in the uprights, and *bent* about the uprights wherever the edge of a sheet does not coincide with one ; a very strong and rigid structure will be the result. Screws are preferable to the spikes usually supplied for fixing galvanised iron, as the structure is to be dismountable. But the galvanised washers also supplied should be used, lest a screw-head should pull through where tension is high. Leave one side of the octagon open—the south side for choice—we shall fix the door there later on It will be rather low, and it will be necessary to stoop to enter if the observer is of average stature. It is, however, no harm, for the humblest observatory is in truth a Temple of the Most High God, and the most exalted of human beings should stoop on entering therein. If 4 ft. be considered too low a doorway, it can be avoided by making the uprights 4 ft. 6 in., or 5 ft., and using galvanised iron of corresponding size. A stouter

timber than the batten is used between these two to make up for the loss of the stiffening effect of the iron sheets. When we have got thus far we may now put in the floor. We fix half a dozen lengths of 3 in. square timber, cut to fit neatly, inside the 8-ft. square. Those which abut on the corner braces should be cut at an angle of 45 deg. at each end, and nailed to the braces. Those running right across are cut off square and a tight fit, and fixed by driving a 6-in. French nail through from outside. If the joists seem to have too much spring a brick or two may be laid under each near the middle. Ordinary flooring boards are then nailed over the joists and frame, being cut away where the iron pier of the equatorial passes through. There should be half an inch clear space between the pier and the boards, to prevent any possibility of vibration being communicated to the telescope by the observer's movements. It is not necessary that the boards should be grooved and tongued. A little space between them will do no harm, as the more ventilation we have in our observatory the better, provided rain and damp are excluded.

CHAPTER XVIII.

The Observatory—(continued).

We have now got so far with our observatory that we have walls and floor, and the circular wall-plate in position. The next step is to provide means to enable the revolving roof to roll on the latter. In the house already described in the "E.M." a circular rail was made of $\frac{3}{8}$-inch round iron rod, secured to the wall-plate with long French nails. The rod was drilled, the holes slightly countersunk, and the nails, which were a tight fit for the holes, had the head cut off and the ends slightly riveted over, so that they were flush with the rod when driven home. On this rail ran three grooved sash-rollers, which were sunk in blocks screwed to the roof. Experience with this dome suggested the following as an improvement. Procure from any ironfounder three rollers of the form shown in Fig. 32. The roller is 2 in. diameter and 2 in. long, and the base is 4 in. square, with a $\frac{1}{4}$-in. hole at each corner to take a screw or bolt. The height from under side of base to top of roller is 3 in. Three will be amply sufficient for an 8-ft. dome.

We also will require four vertical rollers to take the lateral thrust of the dome ; but these need not be either very heavy or very strong, and can be improvised as follows : Get a piece of timber $2\frac{1}{2}$ in. square, and cut from it four 3-in. lengths. Now get six pieces of stout hoop-iron $1\frac{1}{2}$ in. by 2 in. Drill at one end of each two countersunk holes for screws. Close up to the other end drill a $\frac{1}{4}$-in. hole, clamping two pieces together before drilling, so that the holes register exactly. Now screw two pieces to opposite sides of each $2\frac{1}{2}$-in. block, with the ends carrying the $\frac{1}{4}$-in. holes projecting so that the centre of the hole

is about ¾-in. from the end of the block. The iron pieces should be sunk flush into the faces of the block. Cut a 6-in. French nail in two, and slip the head end through the holes in iron. This is the axle of roller. To make rollers cut 2-in. lengths from a broomstick, or turn a piece of wood the right size, and put on it a 2-in. piece of brass tube, a tight driving fit. Bore a ¼-in. hole down the centre, and there is your roller. Slip out the pin made of the half of 6-in. nail, put roller in and replace pin. Screw the arrangement to the wall-plate with roller projecting ½-in. beyond its outer margin. Four of these should be placed equidistant round the circumference.

Now we are ready to proceed with the roof—the toughest part of the job. The first thing we require is a second circle exactly like the wall-plate, but 1 *inch more in diameter outside*. We therefore make the radius of the segments 4 ft. and ½-in. It is put together and screwed in the same way as the wall-plate, with two thicknesses of segments cut from 1-in. plank, the segments in the two layers "breaking joint," as before. When finished hoist it on to the rollers on wall-plate to make sure that it is 1 in. greater in diameter than the latter. Replace it on level ground before beginning the erection of the roof. The roof might be built *in situ*, but it would be less easy to get at.

Now we will have a little exercise in wood-bending. Get a straight-grained piece of matchboard—½ inch stuff, free from knots or defects—and leave it soaking in a pond or ditch for forty-eight hours. If possible to get a 24-foot piece all in one length, so much the better. A 25-foot piece would be better still for our job, for it would go all round the 8 ft. circle and meet; but 24 feet is, I believe, the standard length for a piece. When thoroughly well soaked, it can be bent round the wooden circle

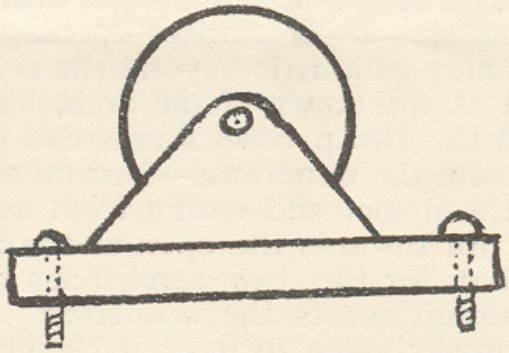


FIG. 32.

and nailed to it, flush at one side and projecting two inches at the other. Where the ends meet bend a 4-inch wide strip of sheet-iron, at least 1 foot long, over it, and fasten with short screws along the edges. The ends of the matchboard strip are its weak spots, and the stout piece of sheeting will prevent it splitting and curling up. A 25-foot strip of sheet-iron, 4 ins. wide, would be be*tter* still, instead of the matchboard, but would be rather expensive. The object of this is twofold. It forms a weather-band, and also a bearing for the vertical rollers to ensure the smooth running of the dome.

If the grooved sash-rollers are preferred, the vertical rollers may be dispensed with, as lateral grip is provided by the grooves on the rolle s gripping the iron rail. In this case we will require to fix four stout iron uprights to four of the eight posts, which uprights must be so bent that they come up above the revolving ring, with a small clearance, and the ends are bent at right-angles, as a safeguard against the lifting of the roof by wind. They will, of course, be fitted last thing of all, after roof is in position. Fit the sash-rollers in blocks of 3-inch timber about 1 foot long, and fix these under the roof ring by a bolt and nut at one end ; but at the other by a screw passing down through the ring from its upper side. If it is at any time required to get at the roller for oiling or replacement, it can be done by levering up the dome and placing a block under. Then withdraw the screw and swing the block carrying the roller inwards till roller is free. The above directions are suitable to such a small observatory as 8 feet diameter and only 4 ft. from floor to ring of revolving dome, in which, therefore, space must be carefully considered and anything projecting inwards is objectionable. In a larger and loftier house we would prefer to fit vertical rollers bearing on the *inner* face of the ring itself' and this is the usual practice.

Now to begin erecting the frame of the hemispherical roof. We shall require *eight quadrants* and *two semicircles* of the same radius as the rings already made, only this time they need not be double. Single 1-inch timbers, with similar curved pieces nailed over all joints, will do. We erect on the roof ring, first, two semicircles 14 inches apart, and parallel, and brace them together with pieces of stout batten, one just behind the crown of the arch and threv or four more at intervals down one half of the semicircle. The other half is left without interruption by cross-pieces, as this is the shutter opening. It is in order that the opening may go a little beyond the zenith that the top cross-piece is not at the crown of the arch, but a little behind it. Having fixed the two parallel semicircles securely in place we proceed to secure the quadrants—four on each side. These are the ribs of the dome, and spring from equidistant points on the ring and run towards the apex of the roof, where they would all unite but for the two semicircles already in place. Where each quadrant meets the semicircle it must be sawn through at the proper angle to meet it cleanly, and be nailed or screwed to it. When the eight pieces are all in position our roof begins to look shipshape. The above width for shutter opening (14 in.) is suitable for a telescope of about 5 in. aperture. A larger instrument would need more to avoid too frequent necessity for revolving the dome.

Now look up the convex pieces which were cut out in making the segments for all these circles and parts of circles. Selecting all the suitable ones, we proceed to cut from them crosspieces to fit between the quadrants of the skeleton dome. Their curve is, of course, approximately the same as that of the quadrants. Being placed horizontally, two, three, or more, in each space between two quadrants and secured by a couple of long French

nails driven through from the opposite side, they greatly stiffen the frame. If we have enough of them to put at least four in each interval between the ribs of the dome, we may lay the ruberoid directly on to the skeleton roof, and it will find support enough in an 8-ft. dome.

But in a larger structure, or in this if we desire a better backing for the ruberoid or other covering, we can *bend on* a casing of matchboard, as we bent the strip which went round the base of the dome. Pick out clean, straight-grained pieces free from knots, cut them to the length necessary to stretch from the base ring at one side to the edge of the semicircle nearest to that side, and put them to soak in a pond or ditch for forty-eight hours. They can then be bent over the curve and nailed to the skeleton frame. They can be made to fit very closely if each piece is sawn in two *diagonally* from top to bottom, thus forming two tapering strips, and each strip nailed on with its broad end down. As these matchboard strips are very liable to split at the ends when nailed, it is a good plan to lay on the end a narrow strip of thin sheet metal—zinc, iron, or tinplate—and nail *through this*. The metal strip keeps all in place even should the wood split. Cut the strip an inch or so longer than the width of the piece of matchboard, and nail down its projecting ends also. At the upper end, where the tapering strips are quite narrow, it is a good plan to nail to the semicircle, outside, pieces of the convex bits aforesaid with the convex edges about 1 in. below the convex edge of the semicircle. This forms a rabbet, in which the ends of the strips can lie, and they can be secured in place by nailing a long strip of sheet metal over them, driving the nails *between* the ends of the pieces of matchboard rather than through them. In the space between the semicircles three whole matchboards can be bent, nailing them to the distance-pieces of batten which brace the semicircle together. It will conduce to the neatness of this job if the battens are not flush with the outside curve of the semicircle, but $\frac{1}{2}$ in. below it, thus allowing the outside of the match-boarding to be flush therewith. When this is done we are ready to fix the ruberoid.

The makers of this material supply cement for joining the edges of the sheets, and galvanised flat-headed nails for fixing it. The latter we may use, but for our present job it is better to employ $\frac{1}{2}$-in. screws, preferably brass, with hemi-spherical heads, and to put wide washers under the screw-heads, as the material is liable to tear away if the nail or screw-heads are too small. If washers are not obtainable of suitable size and material, use narrow strips of thin sheet zinc. There is the advantage in using these that they enable us to confine creases in the material within narrow limits. In stretching a material of limited elasticity on to a hemispherical surface creases are inevitable. But they will do no harm if the edges are well cemented together and the material screwed down to the timber as closely as possible, with a long strip of zinc under the screws to make sure that the heads will not pull through. Cut the

ruberoid into ogival-shaped pieces corresponding to the spaces between the ribs of the roof, each piece going the whole way from the bottom ring to the semicircle. Leave ample overlaps laterally. Cover the two sides first, the ruberoid overlapping the semicircles by a couple of inches, and being bent over them and nailed down inside where it meets the shutter opening. Last of all, cover the space between the semicircular ribs, letting the ruberoid overlap that already laid by at least 2 in. on each side, and cementing it well down. If there is a difficulty in making the edges lie flat use the aforesaid screws and zinc strips, or even tacks, covering their heads with a coat of cement to exclude water. After a day or two the joints will be as solid and weatherproof as one piece.

Last of all, just over the top of the shutter opening fasten, by two long screws going through well into the semicircular ribs, a piece of batten 2 in. by 1 in. or 1½ in., and 2 ft. long. The end of this will project 5 in. on each side of the shutter space, and before screwing down insert two stout screw eyes in the under side about 1 in. from each end. Paint this timber well before putting it in place. A wide strip of thin sheet zinc should be secured all round the bottom of the revolving roof, overlapped about 1 in. by the lower edge of the ruberoid, and forming a weatherband covering the wall-plate.

CHAPTER XIX.

The Observatory—(continued).

Last but not least in importance is the shutter. The type of shutter described by Berthon, Chambers and others is heavy, clumsy, very lable to be lifted or damaged by wind, and very doubtfully weatherproof. A roll-up shutter, of canvas, has been used by the writer now for many years, first on the 8-ft. and afterwards on the 15-ft. domes, and has given entire satisfaction. A strip of the strongest sail-makers' canvas is obtained, a little longer than the shutter opening, in the case of the 8-ft. dome, 7 ft. long. This canvas is made 2 ft. wide, and this will just suit our 14-in. opening, covering it and overlapping 5 ins. on each side.

Next we obtain, from the sailmakers or yacht outfitters, two dozen brass eyelets, " grummet rings " I believe the sailors call them. These are sold each ring in two parts, a flat ring, like a thin washer, and a conical one. To insert them, a hole is made in the canvas by pushing a blunt iron spike through it, the nose of the conical ring is pushed through the hole, the flat washer placed over it, and then the conical part is expanded by driving a smooth blunt-pointed steel cone into it. The centre of a lathe does first-rate for this job, especially if it is a 60 deg. centre. When expanded enough to grip the washer the ring is hammered down with a convex-faced hammer till it is riveted over firmly and the canvas is gripped between the two parts. A dozen of these eyelets must be fixed at equal

intervals just within the selvedge of the canvas at each side. We also fix half a dozen pieces of very light lath across the width of the canvas. Each is 16 ins. long, and is attached by two small brass screws, with washers under their heads, driven through the canvas from the other side. At one end of th canvas it is nailed securely with flat-headed nails (those supplied for fixing the ruberoid, being galvanised, are excellent) to a stout wooden roller 3 ins. in diameter and 3 ft. long. This is the lower end of the shutter. The upper end is nailed with the same flat-headed nails to the under side of the batten already mentioned, which is fixed across the roof just above the top of the shutter opening. If already fixed it must be dismounted to nail the canvas to it and replaced. In addition to the two screw-eyes already mentioned in its under surface, two more must now be fixed on its upper side. The distance apart of the screw-eyes on the under side must be 22 ins., 2 ins. less than the width of the canvas, as these take the line which is to be rove through the eyelets therein. The screw-eyes on the upper side should be about 28 ins. apart, as they carry the rolling-up line, which passes round the projecting ends of the roller, outside the canvas.

Lastly, we make a pair of thick wooden discs, preferably of hard wood. They should be about 4 ins. diameter and should be finished nice and smooth. One of them is to be fixed on each end of the roller, by two long screws. (See Fig. 33).

Next we require a pair of metal links of the shape shown in Fig. 34, which is a face view of one roller. One of these is affixed *loosely* to the centre of each roller by a screw through

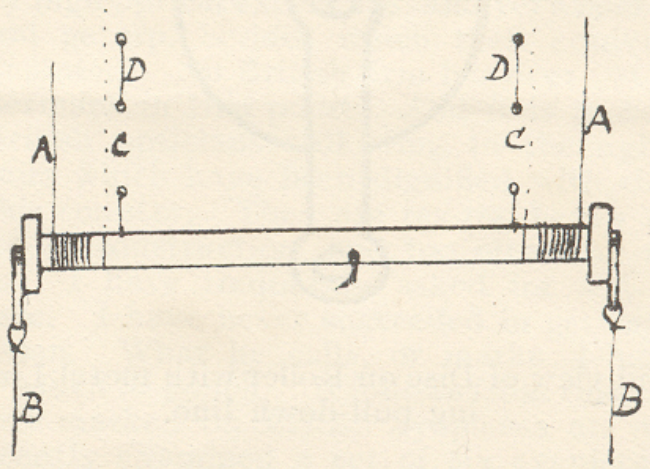


FIG. 33.—The Roller and its Fittings.—The dotted lines C.C. are edges of canvas. A.A. are the rolling-up lines. B.B. the pull-down lines. D.D. the holding-down lines, passed in and out of the eyelets. Short pieces of light lath (not shown) attached to the under side of canvas at intervals of 1 ft. or so, and a little longer than with of shutter opening, keep canvas from sagging.

one end. The other end hangs down vertically, whatever the position of the roller, on account of the loose fit of the affixing

screw. To the lower ends of these the ends of the pull-down line are fixed. When the batten carrying the upper end of the canvas is fixed in position we can proceed to fit the lines. For these cod-line is excellent. It is about $\frac{1}{4}$-in. diameter, and very strong, and will stand years of exposure to the weather. If desired, it may be tanned. Steeping in strong tea is an easy way of doing this. The lines are in pairs, one line to each side of the canvas. We may call them (*a*) the "holding-down" lines; (*b*) the "rolling-up" lines, and (*c*) the "pull-down" lines.

(*a*) The holding-down lines are rove through the eyelets, one end being fastened securely to the bottom roller just inside the edge of the canvas. From this the line proceeds in and out through the eyelets, and after leaving the last of them, passes through the screw-eye on the *under* side of the top batten. It then is led down the back of the dome, and made fast to a cleat just above the weatherband of the roof. Its office is to *hold down* the edges of the canvas, lest it be lifted by wind.

(*b*) The "rolling-up" lines are rolled round the projecting ends of the roller in such a direction that a pull on them causes the roller to roll upwards, rolling up the canvas as it does so. They are carried from the roller through the two screw-eyes on the upper side of the top batten, and from thence down to the

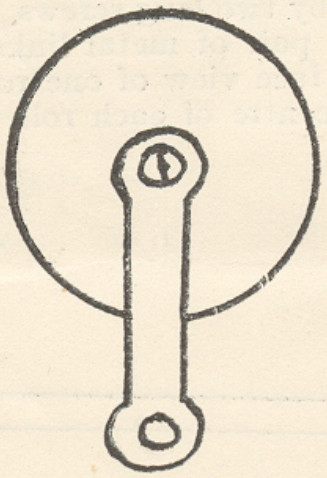


FIG. 34.—End view of Disc on Roller with metal Link for attaching pull-down line.

same cleat as before, or another close to it. To roll up the shutter all that is necessary is to pull evenly on these two lines till the canvas roll is stopped by the batten at the top of dome.

(*c*) The pull-down lines are attached to the lower ends of the two metal links aforesaid, and their office is to pull down the canvas shutter when closing the dome. A pair of cleats are fixed just below the two ends of the roller as it lies when down, and to these the pull-down lines are made fast. The two lines in each pair should be in one continuous piece, the piece being long enough to reach the distances required, with a few feet to spare.

To open shutter : (1) Cast off " pull-down " lines from their cleats ; (2) Go to back of dome and cast off " roll-up " lines ; (3) Pull on latter till shutter is right up and make line fast again. To pull down, reverse the proceeding. The discs on ends of roller are to prevent the roll-up lines slipping off and fouling the pull-down. The final operation of all is to give the canvas a coat of a mixture of equal parts boiled and raw linseed oil. It is then absolutely waterproof, and the perforations made by the little screws which attach the pieces of lath to keep it flat are completely sealed. These strips of lath are inside and rest at each end on the edges of the shutter opening, being 2 ins. longer than its inside width. Their ends should be bevelled off on the side next the canvas to prevent chafiing holes in it.

CHAPTER XX.

EYEPIECES.

I do not propose to treat of *making* eyepieces. An amateur who is clever with his lathe *may*, no doubt, make them ; but it is quite certain that he could buy them more cheaply than he could make them, and of much better quality. Before the war German eyepieces by the firms of Carl Zeiss and Steinheil Sohne could be purchased for 10s. each in the Huyghenian form, and the same two firms offered a large variety of other types at prices from 15s. to 30s. each according to construction. These were all of very high optical excellence, and very neat and handy in their general get-up, besides which their equivalent focus was accurately stated. No British firm has ever yet attempted to beat the Germans in this point. And it is to be regretted that so far British opticians still cling to the ugly, clumsy, haphazard affairs which have been dignified with the name of eyepieces in this country. They are far too heavy and bulky, of little variety of construction, and too often are thrown together anyhow. I have frequently asked for a $\frac{1}{2}$-inch Huyghenian eyepiece. I have never succeeded in getting one from a British optician. What he calls, or marks, $\frac{1}{2}$-inch may be anything from $\frac{3}{8}$-inch to $\frac{5}{8}$-inch. It follows from this carelessness that the powers marked on British eyepieces are wholly unreliable. I recently examined a set of six eyepieces supplied with a 5-inch refractor to a well-known F.R.A.S. by one of our greatest optical houses. The object-glass was a superb example of the firm's work, a perfect gem. But the less said about the eyepieces the better. Optically they were of fair quality. They did not actually spoil the definition of the magnificent objective : but regarded as powers they were just anyhow. They were marked 80, 120, 180, 240, 280, 350. This series, *if correct*, would be excellent for a 5-inch telescope, and would only need the addition of an extra low power of about 30 or 40 to make it ideal. But the dynamometer revealed a curious state of affairs. The reputed " 80 " was over 100. The " 120 " was

116 (not a very serious discrepancy if it had stood alone). The "180" was 220. The "240" was also 220. The "280" was 250, and the "350" was 280. So the possessor had only five powers instead of six, and those five were badly distributed: 102, 116, 220, 250, and 280. He had nothing which could be called a low power. In the most useful part of the telescope's range, that between 120 and 200, he had nothing at all. And his last three powers were so close together as to have little useful difference between them. And he had nothing above 56 per inch aperture. All the best capabilities of his objective, in fact, were wasted, and he had a useless duplicate eyepiece in his set. I have no doubt that very many telescopes are sent out in the same condition. It therefore behoves any observer who desires to get the best out of his telescope to see that he has a suitable set of eyepieces, and to choose his powers himself and verify them carefully.

And here let me say that one of the first necessities for "getting the best out of" a telescope is to have a suitable power for the *lowest* of the set. And by a suitable power I mean a power near the lowest which the aperture will take without loss of light. That is to say, one in the neighbourhood of 5 per inch aperture. A power so low as this will require to be fitted into a separate draw-tube, of ample size, in order to accommodate the large field lens which must be provided if the field of view is not to be cramped. The draw-tube of an astronomical telescope should never be less than $1\frac{1}{4}$ in. diameter, and $1\frac{3}{4}$ in. would be better still. The full size of this tube will be required to contain the field-lens of a suitable low power. The eyepiece may be arranged to slide into the draw-tube, after unscrewing the fitting which takes the higher powers; or else a second draw-tube may be provided, sliding into the same place as the usual one, and carrying the lowest power.

The telescope is primarily an illuminating or light-gathering and light-concentrating instrument, rather than a magnifying one. And when one has once enjoyed the sight of such objects as Theta Orionis and its surrounding nebula, the Chi Persei cluster the great Andromeda Nebula, the Pleiades, and others of the same class, with a real low power, and a large field, one does not willingly put up with a set of eyepieces the lowest of which is high enough to dilute these glorious galaxies and lose half their beauty. The lowest power usually supplied with ordinary telescopes of 3 to 5 in. aperture is about 50 to 70, and is nowhere near low enough. A 3 in. telescope should have a lowest power of not more than 20, and a 5 in. should begin with 30.

I give here a few sets of powers suitable for telescopes of common sizes. It will be noticed that the larger the aperture the larger the assortment of powers desirable. The last set would do also for a 6 in.

For a 3 in.:—

Two powers	40, and 100, or 50 and 120.
Three powers	30, 60, 120, or 30, 80, 140.
Four powers	20, 60, 120, 180.

For a 4 in. :—

Three powers	40, 80, 160.
Four powers	40, 80, 160, 220.
Five powers	25, 70, 112, 180, 250.
Six powers	25, 60, 100, 150, 200, 300.

For a 5 in. :—

Three powers	50, 100, 200.
Four powers	40, 80, 120, 200.
Five powers	30, 80, 120, 180, 250.
Six powers	30, 80, 120, 180, 250, 400.

Six or seven powers are sufficient for almost any telescope, whatever it aperture. And we must remember that as we increase aperture, especially with reflectors, the highest power per inch aperture which the telescope will bear falls off rapidly. For example, an 8½ in. mirror will probably bear a power of 400 on extra good nights. But it does not follow that a 16 in. one will bear 800. It is more than likely that the 16 in. will not bear 400 as well as the 8½ in. does. But then a 16 in. will see more with 200 than an 8 in. will with 400. The 18 in. Calver reflector in the present writer's possession had a noble battery of eyepieces with it in a lovely mahogany case. There were nine of them, beginning with 100 and going up to 1,200. But six out of the nine might as well have been omitted. It was very rarely that it was possible to use more than 200 on it, and never more than 500. The last three of the set were totally useless on any telescope, the highest being 1-12th in. equivalent focus.

The foregoing remarks apply to the common negative or Huyghenian eyepiece, the only ocular known to nine out of ten amateur astronomers. And for general star-gazing purposes nothing better exists. Moreover, the Huyghenian has the great merit of being to a slight extent a " compensating " eye-piece—*i.e.*, though nearly achromatic, its slight departure from achromatism helps to correct the secondary spectrum of the refractor, especially if the objective be, as very many are, a little over-corrected for colour. On a reflector a keen eye soon recognises the defective achromatism of the Huyghenian and will prefer some one of the achromatic eyepieces, such as Browning's, or the cemented combinations formerly made in Germany. Achromatic eyepieces do not work well on a refractor, the secondary colour of the object-glass being far more obtrusive when they are used. The Huyghenian eyepieces of Zeiss and Steinheil already mentioned are also better suited to the reflector. The writer has had plenty of experience of these facts, having worked side by side for several years the 18 in. Calver reflector and a 5¼ in. refractor. During part of the time the two instruments were mounted as a twin, both being on the one equatorial stand. Each had its own battery of eyepieces, the 18 in. having the 9 Huyghenians above-mentioned, and the 5¼ in. a set of six, some of them by Steinheil and others by Zeiss. The highest was a 5 mm. " orthoscopic " by Zeiss, an achromatic combination of very large field and fine optical quality. Well, it was not long before the two telescopes had exchanged batteries, the Huyghenian going to the refractor and the German set to the big mirror, and so they remain.

The highest power commonly purchaseable is 1-5th in., practically the same focus as the above 5 mm. This will give × 300 on a normal 4 in. o.g., about enough for any but an exceptionally fine lens of that size. On a mirror of unusual excellence or a short-focus o.g., it may be desirable to have a 1-6th or 1-7th in. eyepiece, but such have usually to be made to order. And it is well to order only from a firm of well-known merit, such as Dollond or Grubb. The ordinary optician (or "shoptician"), if asked for a 1-6th in. eyepiece, will throw any sort of rubbish he may happen to have in stock at you. As likely as not you will get a ¼ in., and maybe a bad one at that. A good eyepiece of this short focus will probably cost 30s., and is worth it.

It is hardly necessary to deal with eyepieces other than Huyghenians, when writing for amateurs. The achromatics of Browning and Zeiss have already been mentioned. Steinheil Sohne formerly strongly recommended a combination known as "monocentric." It was a cemented achromatic system similar to the aplanatic pocket magnifiers supplied by the same firm, and also produced by Browning. They were very fine eyepieces, both in high and low powers, but a good deal more expensive than Huyghenians. The Ramsden eyepiece, commonly employed in finders, makes a good low power, but is not achromatic. Old-fashioned English *microscope* eyepieces may often be picked up almost "for a song," and make tip-top low powers for the telescope. They were made for wide tubes, and consequently have fine large field lenses and ample fields of view for comets, clusters, etc. They are well worth the trouble of adapting to the draw-tube of an astronomical telescope; 1½ in. or 2 in. equivalent focus is a common size.

Occasionally one comes across a Galilean eyepiece (a double-concave lens) employed as a high power. I believe Grubb is partial to this construction for his highest powers; at least, any I have seen have been his. It has the same merit as the Huyghenian of reducing the secondary colour in a refractor, and, being a single lens, and a thin one at that, it is economical of light. It should, therefore, do well on faint *comites* to double stars.

So much has been written in books for amateur astronomers on eyepiece construction and the optics thereof that I have not thought it necessary to repeat matter given by Webb, Denning, Chambers, and many others. Suffice it to say, that the Huyghenian eyepiece consists of two plano-convex lenses, having their plane sides both towards the eye. The focal lengths of these should theoretically be as 1 : 3, the eye-lens being the shorter, and their distance apart should be half the sum of their focal lengths. These dimensions are, however, rarely adhered to in practice. The German form of Huyghenian had a meniscus field lens with the concave side towards the eye. The Ramsden eye-piece is simply a pair of equal plano-convexes, with their convex sides next each other and separated by a distance slightly less than the focal length of either. The Kellner construction, sometimes used for low powers, has a

double convex field lens with radii as 2 : 3, the deeper curve being towards the object-glass, and a plano-convex eye-lens, placed as in the Huyghenian, and distant its own focal length from the field lens. Browning's achromatic eyepieces are Kellners, with an achromatic combination for eye-lens, the side next the eye being concave.

To ascertain what are the powers of a set of eyepieces, a dynamometer is necessary. The most usual and cheapest form of this useful little instrument we owe to the Rev. E. L. Berthon. It consists of a pair of metal straightedges, fixed at a very acute angle to each other, one edge being provided with a scale of 1-100 in. divisions, showing the distance between the edges at each division. It can be used as a wire gauge, or to measure the thickness of sheet metal, etc. As a telescopic dynamometer it is used by measuring the diameter of the "Ramsden disc." If the telescope be directed to the open sky, a sheet of white paper, a whitewashed wall, etc., the eye placed about 12 in. behind the eyepiece, sees in it the image of the object-glass as a sharp bright disc. This is the "Ramsden disc." Being a real image, and in front of the eye-lens, it can be focussed with a magnifying-glass or pocket lens, and a very sharp view of it obtained. The dynamometer is now placed in position and adjusted till each edge is tangent to the disc of light. The scale is read at the point of contact. The aperture of the telescope, divided by the diameter of the Ramsden disc, gives the power of the eyepiece on that particular telescope or any other of the same focal length. A telescope is not even necessary for the measurement. The image of a window-pane, clock-dial, or any other sharply-defined object can be used, and the result will be the power of the eyepiece on a telescope whose focal length is the distance of the eyepiece from the object used. Then, taking this power as a divisor and the focal length as a dividend, the quotient is the equivalent focus of the eyepiece. For example, on a 5 in. telescope the Ramsden disc was 1-10th in. diameter. Power was therefore 5 in. ÷ 1-10th = 50. The focal length of the o.g. was 75 in. : 75 ÷ 50 = 1.5. Equivalent focus of eyepiece was $1\frac{1}{2}$ in.

Again, with another eyepiece on same telescope, the Ramsden disc measured 0.03 in. Power was therefore 5 ÷ 0.03 = 166. Equivalent focus of eyepiece was 75 ÷ 166 = 0.45 in.

It is necessary, before making these measures, to make sure that the aperture of the o.g. is "clear"—*i.e.*, that none of the stops in the tube are narrow enough to stop any portion of the cone of light converging from it. Any other instrument capable of giving an accurate measurement of the diameter of the Ramsden disc can be used as a dynamometer, an ordinary micrometer calipers being an excellent substitute, especially if its two contact faces are lightly smoked in a candle flame to prevent reflection from them. It is sometimes stated that the equivalent focus of a Huyghenian eyepiece equals half the focal length of its field-lens. If this were true it would be easy to measure powers, as the field-lens, being the larger of the two, has a fairly long

focus and easily measured directly. But, unfortunately, it is only true if the proper proportions for a Huyghenian (foci as 1 : 3 and distance apart = 2) are strictly adhered to by the makers, which they rarely, if ever, are.

It may be well to state, in conclusion, that the equivalent focus of any two-lens eyepiece can be obtained from the formula :

$$\frac{f_1 \times f_2}{f_1 + f_2 - d}$$

where f_1 and f_2 are the focal lengths of the components, and d their distance apart. The distance apart of plano-convex lenses should be measured from their *convex* faces, not from the plane ones, as might *prima facie* be supposed. The only drawback to this formula as a means of measuring powers is the difficulty of obtaining an accurate measure of the focus of very small lenses, such as the eye-lenses of high powers always are.

Since the first edition of this little book was published, some British firms have begun to manufacture eye-pieces on the German model, and with excellent results. But prices, which went up during the war, have stayed up: and good quality eye-pieces cost 30/- or more.

An important fact, but little known, is that compensating eye-pieces, as made for the microscope, will vastly improve the performance of an object-glass which is under-corrected for colour, a not uncommon fault in second-rate lenses.